CRANFIELD UNIVERSITY

MATTHIAS AUTZEN

SET-BASED CONCURRENT ENGINEERING APPLICATIONS

SCHOOL OF APPLIED SCIENCE
M.Sc. Thesis

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Supervisors:
Dr. Ahmed Al-Ashaab and
Dr. Essam Shehab

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ABSTRACT

Engineering companies must improve their product development performance in order to meet the challenges of the 21st century where R&D activities are coming more and more under pressure of productivity demands.

Lean thinking is an improvement philosophy, which focuses on the creation of customer-defined value and the elimination of waste. The application of lean techniques to manufacturing and production processes has helped western engineering companies to stay competitive against their counter-parts from low-wage countries in the last 20-30 years. However, compared to lean manufacturing, relatively little research has been conducted in the field of lean product and process development.

Set-based concurrent engineering is advocated to be one key enabler for lean product and process development and seemed to be a promising approach to enhance product development projects with several potential benefits in relation to conventional approaches.

This research project focuses on synthesizing the good practices of set-based concurrent engineering within the context of lean product development, formally embedding certain set-based methodologies into an existing product development process of a company whilst defining a step-by-step guideline how to do it. Finally the new transformed development process model shall be applied in a case study in order to evaluate its practical applicability as well as the advantages and disadvantages.

After synthesising the good practices of lean product development and set-based concurrent engineering through an extensive literature review a field study in the collaborating company has been conducted. With the help of a developed questionnaire the current practices have been analysed against the SBCE principles with the goal to identify the challenges and opportunities for improvements. Considering the results of the field study a new transformed set-based product development model has been defined guided by a developed step-by-step transformation methodology. Finally the new transformed product development process model has been evaluated in a real industrial case study in order to give an assessment of the practical applicability as well as advantages and disadvantages of the SBCE approach.

This research provides a practical approach of a step-by-step transformation methodology to support companies to integrate the SBCE good practices into their traditional PD model. The transformed product development process model contains several new aspects that enforce innovation and creativity as well as decreasing the risk of rework at later stages of the process.

Keywords:

Set-based concurrent engineering, LeanPPD, Product development, Lean transformation

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LIST OF ABBREVIATIONS

SBCE	Set-based concurrent engineering
WIPO	World intellectual property organization
PD	Product development
R&D	Research & Development
NPI	New product initiation
NPD	New product development
QG	Quality gate
EPM	Existing development process
FMEA	Failure mode and effects analysis
FTA	Failure tree analysis
KVA	Key value attribute
TRIZ	Theory of inventive problem solving
PDM	Product data management
FEA	Finite elements analysis
RAMS	Reliability, availability, maintainability, safety
LCC	Life cycle cost
EMC	Electromagnetic compatibility
IP	International protection

1 INTRODUCTION

1.1 Background and approach

The business environment for engineering companies has changed dramatically over the last few years. Whilst formerly the focus was on optimisation of production processes in order to stay competitive, today R&D activities and new product development are coming more and more under the pressure of productivity demands due to increasing world-wide innovation competition. The World Intellectual Property Organisation (WIPO) noted a geographic shift in innovation activity from North America and Europe to middle-income countries in Asia, mainly to China. Overall, Asian patent applications accounted for 39 per cent of those filed in 2010, while North America accounted for 28.3 per cent and Europe for 13.9 per cent (http://www.reuters.com, 2012).This is a significant indication that the low and middle-income countries are no longer the workbenches of western companies but building up their own technology and products.

The application of lean techniques to manufacturing and production processes has helped western engineering companies to stay competitive against their counter-parts from low-wage countries in the last 20-30 years. Applying lean thinking methodologies to streamline a repetitive manufacturing process is relatively easy, because the actual product can be traced and waste is visible and can be determined (Turner, 2002). In contrast to manufacturing, a product development project is a unique task with a non-repetitive character. A certain degree of variability and flexibility is intended to encourage and stimulate creativity. There is usually no visible product existing in the concept phase and therefore it is difficult to trace or measure productivity.

Up to 70-80% of manufacturing costs are determined very early in the concept phase of a development process, usually without real transparency to cost, quality and degree of requirement fulfilment (Eversheim, 1997; Lenders, 2009). Additionally, design changes during a development project normally take 30-

50% of the total project costs, sometimes as much as 70% (Ehrlenspiel et al., 2005; Lindemann et al., 1998; Lenders, 2009). A significant proportion of design changes usually occur in the later stages of a development project which increases the risk to the "time-to-market" as well.

However, compared to lean manufacturing, relatively little research has been conducted in the field of lean product and process development. The work that has been done also goes back to Toyota, as with lean manufacturing. Ward (1995) and Sobek et al. (1999) studied and documented the Toyota Product Development System and found the so called "Set-Based Concurrent Engineering" approach as one key enabler for Lean Product and Process Development. This means that design participants reason about, develop and communicate sets of solutions in parallel and relatively independently. As the design process continues they gradually narrow their respective sets of solutions based on additional information from development, testing, the customer, and other participant's sets. As designs converge, participants commit to staying within the set, barring extreme circumstances, so that others can rely on their communication (Sobek et al., 1999). However, the authors themselves realised that this approach is not properly documented and therefore more a philosophy than a defined process. No recipe exists regarding how to implement Set-Based Concurrent Engineering to an existing product development process and there is still no evidence that such an approach would bring benefit to a company outside Toyota.

As part of the collaborative European research project titled "Lean Product and Process Development" (LeanPPD), which is supported by the European Commission for Research and managed from Cranfield University, UK, an SBCE baseline model has been developed, which builds the foundation of the worked presented in this thesis.

This research project focuses on synthesizing the good practices of set-based concurrent engineering within the context of lean product development, formally embedding certain set-based methodologies, based on the SBCE baseline model, into an existing product development process whilst defining a step-by-step guideline how to do it, and finally apply the new transformed development process model in a case study in order to evaluate the practical applicability as well as the advantages and disadvantages.

1.2 Research aim and objectives

The aim is of the research is to enhance the product development process by integrating the good practices of set-based concurrent engineering (SBCE) to develop a customised new product development model.

The following are the main objectives of the research which are to:

a.) Synthesise the good practices of the lean product development and set-based concurrent engineering through an extensive literature review.

b.) Analyse the current product development practices within the collaborating company and to identify the challenges and opportunities for improvements.

c.) Adopt the SBCE baseline model in order to develop a customized new PD model that is suitable for the specific needs of the collaborating company.

d.) Evaluate the customised SBCE model via real case study and expert judgement and give an assessment of the practical applicability as well as advantages and disadvantages of the SBCE approach.

1.3 Thesis structure

This section provides a brief overview of the thesis structure and the chapter content in order to understand the methodology of the research:

Chapter 2 Literature review: The result of an extensive literature review is presented in Chapter 2. The different concurrent engineering approaches have been explained. The advantages of SBCE, the challenges for the implementation, the enablers which support its application as well as the principles of the SBCE baseline model are identified.

Chapter 3 Research outline: The research gap and the research methodology have been defined. The intention of the research methodology and the defined key tasks and deliverables (Figure 3-1) was to create a general overview of this research and to guide the author through the work to be performed.

Chapter 4 Field study: Based on the findings of the literature review a questionnaire has been developed which is structured corresponding to the different phases of the SBCE baseline model. With the help of this generic questionnaire a field study in the collaborating company has been conducted. The objective of this field study was to analyse the current product development practices within the collaborating company in relation to the set-based concurrent engineering (SBCE) principles. The result of the field study has been presented in Chapter 4.

Chapter 5 SBCE baseline model transformation: A formal approach has been developed regarding how to integrate SBCE into an existing development process. The generic transformation process applied in the collaborating company has been documented in Chapter 5, guided by the developed step-by-step approach of the author.

Chapter 6 Industrial case study: An industrial case study has been conducted and documented in Chapter 6. The aim of this case study was to pilot a real industrial project in order to evaluate the newly defined PD model developed in Chapter 5.

Chapter 7 Conclusion and discussion: The contribution to the knowledge, the potential benefits of the newly defined set-based product development model as well as the shortcomings and disadvantages are presented in Chapter 7.

2 LITERATURE REVIEW

2.1 Overview and history of lean in product development

“Lean” was initially introduced in the book “The Machine that Changed the World,” by Womack, Jones and Ross in 1991. The authors described the leanness of the Toyota production system which, in contrast to traditional mass production, is based on the principles of just-in-time and building only the parts needed for the next production step when they are needed based on a “pull-system” (Liker and Morgan, 2011).

In subsequent years the concept of Lean Thinking has attracted many researchers and practitioners from all over the world, the main focus being applications to production and manufacturing processes, with great success. In the automotive industry for example,, the manufacturing productivity gap shrunk from 16.5 hours per vehicle in 1996 to 7.33 hours in 2005 (Teresko, 2007; Bimal et al., 2011). As lean manufacturing today is already widely established in the industry, it is no longer an order winning strategy in the global competition (Bimal et al., 2011).

However, in “The Machine that Changed the World” Womack et al. also dedicated one chapter of 30 pages to the idea of Lean Design and Lean Product Development, based on the findings of Clark, Chew, Fujimoto and Sheriff in the late 1980s (Hoppmann et al., 2011). The following elements were identified as key techniques: a powerful project leader with strong authority, early and controlled communication and simultaneous (concurrent) development (Womack et al., 1991).

In comparison however, in the manufacturing field relatively less research and application has been conducted in the area of Lean Product Development. This is rather strange because “Product Development by definition plays a key part in defining customer value. It determines the physical appearance of the product defines the material to be used, largely constrains the set of production processes that can be employed to manufacture the product. Consequently, the impact on cost, quality, and manufacturing lead-times is usually much bigger in the phase of PD than during production" (Morgan and Liker, 2006; Hoppmann et al., 2011).

A few researchers have created general frameworks of what they claim to be the definition of Lean Product Development, but the literature still lacks a single accepted definition:

- Ward (2007) defined five building blocks of LPD principles
- Morgan and Liker (2006) published their findings in the Toyota PDS, in which the authors identify thirteen Lean PD principles grouped into three categories: Process, People and Technology
- Schuh et al. (2008) described ten key principles for efficient product development
- Brown (2007) listed thirteen components he identifies as having the largest impact on improving performance on PD
- Hoppmann et al. (2011) created a framework consisting of eleven Lean PD components

Set-Based Concurrent Engineering, the focus of this research, has been identified as one of the most promising techniques to enable Lean Product Development by almost all leading researchers in the field of Lean Product Development. Set-Based Concurrent Engineering comprises of a number of characteristics including exploring multiple alternatives, delaying specifications, a minimal constraint policy, extensive prototyping (or simulation), and convergence upon the optimum design.

As part of the collaborative European research project titled "Lean Product and Process Development" (LeanPPD), Khan et al. (2011) developed a newly defined SBCE baseline model, which they believe will address some of the key challenges faced by engineering companies in the 21st century. Their findings are building the foundation of this research and will be further described and explained in Section 2.7.

2.2 Importance of efficiency in product development

R&D activities and new product development are coming more and more under pressure of productivity demands due to several reasons.

In many business sectors the number of products segments increases. As a consequence, the number of product variances in the portfolio of a company is increasing while the number of pieces per model is decreasing. This in turn leads to higher R&D cost per product compared to previously, meaning decreased return of investment per product (Schuh, 2009). In addition, the product life-cycles are shortening with a decreased tolerance for quality issues. Lengthy rework efforts after product launch are less acceptable for a short life-span than for a longer one (Morgan and Liker, 2006; Hoppmann, 2011). Supplementary markets tend to be rather oligopolic, which makes technological advance even more important.

In contradiction, new product development activities are still underperforming when compared to manufacturing. For instance, a study by MIT (McManus, 2003) has shown that 77% of New Product Introduction (NPI) activity is pure waste (Parry and Turner, 2004).

The fact that 70-80% of product costs are determined very early in the concept phase of a product development process, usually without real transparency to cost, quality and degree of requirement fulfilment (Eversheim, 1997; Lenders, 2009) indicates a clear need for an efficient product development process. In addition, design changes during a development project normally take 30-50% of the total project costs, sometimes even 70% (Ehrlenspiel et al., 2005; Lindemann et al., 1998; Lenders, 2009). A significant proportion of design changes usually occur in the later stages of a development project which is a risk to fail the “time-to-market” as well. The explanations above clearly indicate that the key to success for engineering companies lies in productivity improvement within their product development system.

2.3 Concurrent Engineering approaches

2.3.1 Concurrent Engineering

"Concurrent Engineering is the integrated and parallel execution of Product and Process Development with the intention of shortening the period from the initial product idea to the final product release (Time-to-market), to reduce development and production cost and to enhance the overall quality of the product" (Eversheim et al., 1995; Lenders 2009).

The fundamental research on Concurrent Engineering has been conducted by Clark et al. (1987), who found that "Japanese Product Development projects made use of overlapping development stages to a larger extent than projects in European or American car manufacturers. The hypothesis that this overlap could contribute to significantly shorter lead-times was subsequently confirmed by follow-up analyses by Fujimoto, Clark, and Sheriff" (Hoppmann, 2011). Concurrent Engineering means to start a process step at the earliest possible point in time both in horizontal as well as in longitudinal direction: "Concurrent engineering is inherently about horizontal coordination across functions (e.g. managing the interfaces of subsystems) and longitudinal coordination across development stages (e.g. interface between product design and manufacturing)" (Khan et al.,2011). The application requires high coordinative and communication effort in the form of cross-functional teams and meetings in order to align abilities and constraints of the organisational stake-holders such as design engineering, manufacturing, quality and procurement (Hoppmann, 2011; Sobek et al., 1999).

Concurrent Engineering is widely advocated as essential to successful product development programs (Liker et al., 1996). One example of concurrent engineering is to start the mould construction, often with early supplier involvement, before the part drawings are finally released based on a given tolerance range. Concurrent Engineering processes may be classified as "point-based’’ and "set-based" depending on how soon the initial set of conceptual ideas converge (Sobek et al., 1999; Ford and Sobek, 2005).

2.3.2 Set-based concurrent engineering approach

“Traditional design practice, whether concurrent or not, tends to quickly converge on a solution (a point in the design space) and then modify that solution until it meets the design objectives. This seems an effective approach unless one picks the wrong starting point” (Sobek et al., 1999). In contrast to that traditional approach the philosophy behind SBCE is to consider a large number of possible solutions for each product module at the front-end of the Product Development Process. Instead of quickly narrowing down the set of alternative solutions, engineers design, test, and analyse multiple solutions for every subsystem in parallel (Morgan and Liker, 2006). The main intention of this approach is to validate and verify possible design options through comprehensive evaluation, prototyping, testing and simulation, in order to make a judgement about a solution based only on facts and an objective data basis relative to functionality, cost, quality and degree of requirement fulfilment. Only when, based on objective criteria, a solution has been proven to be inferior to other designs, is this design removed from the solution space (Schuh et al., 2007). In this way, the set of alternatives is gradually narrowed down and finally converges to a single solution (Ward et al., 2007). Once the engineers have decided on a particular design, this solution remains unchanged until the start of production, unless altering the module is absolutely necessary (Ward et al., 1995; Hoppmann, 2011). Khan et al. (2011) illustrated the set-based concurrent engineering approach as shown in Figure 2-4.

“Set” can be defined as the number of design options. The set of possibilities might include a number of discrete designs or a range of parameter values (Liker et al., 1996). Ward et al. (1995) explained that Toyota intentionally uses a "rapid inch-up" strategy to keep many of the subsystems and components essentially the same, while selectively innovating. Many of the design decisions they have described as set-based are in fact, incremental, fine-tuning for the sake of fit and finish, marginal performance improvements, or weight/cost reductions. Sobek et al. (1999) explained that "sets might also be bounded intervals for parameters (noise reduction will fall somewhere between fifteen and thirty decibels) or open-ended intervals (this part needs at least x cubic cm of space)."

For this research "Set" will be defined as reasonable number of alternatives relative to product functionality, manufacturing process or dimensions and tolerances. This means that whatever the actual task for the development engineer, he should intentionally explore the design space and evaluate different options before deciding on a final concept.

2.3.3 Advantages of set-based concurrent engineering

The key advantages of SBCE identified and extracted during the literature review have been listed below:

- Avoidance of time and cost consuming engineering changes late in the development process (Lenders, 2009)
- Early and critical decisions based only on data instead of subjective guessing (Ward et al., 1995)
- Communicating whole sets of possibilities simultaneously ensures that communication and decisions remain valid throughout the project's life (Ward et al., 1995)
- SBCE assumes that reasoning and communicating about sets of ideas leads to more robust, optimized systems and greater efficiency than working with one idea at a time, even though the individual steps may look ineffective (Sobek et al., 1999)

- Focusing on convergence, rather than on tweaking a good idea to optimize it, can dramatically reduce the amount of back-tracking in the process (Sobek et al., 1999)
- Toyota has a high regard for the learning acquired in working on multiple ideas. It seems to have faith that the skills and knowledge generated will pay off later, either directly through incorporation into the next project or indirectly through expanded skill sets and knowledge (Sobek et al., 1999)
- A lot of knowledge is gained from all the alternatives explored by applying SBCE (Ward et al., 1995)

2.3.4 Set-based concurrent engineering enablers

This section explains tools and enablers within the SBCE environment which can be considered as the most popular ones based on the findings from the literature review.

Design/project concept document: Within the Toyota organisation the Chief Engineer is responsible for the production of a design concept document, which is used to communicate the vision for a product. The concept paper lines out the vision for a new vehicle and includes both quantitative and qualitative objectives for the product characteristics, performance, cost and quality (Morgan; Liker, 2006). The concept paper is used to translate the voice of the customer into specific goals for the engineering structure of the company and to create a common understanding of the goals of the project. “The concept paper is the result of many months of discussion, information gathering and consensus building and has been approved by the managing directors of the company”. Once approved it becomes the law of the program (Morgan; Liker, 2006).

Engineering checklists: Part specific checklists are considered to be one key enabler for lean product development and SBCE in special. Sobek et al. (1999) described the purpose of engineering checklists as follows: "Every engineering function maintains checklists that detail design guidelines in any number of areas including functionality, manufacturability, government regulation, reliability and so on. The descriptions may also contain descriptions of what can and cannot be economically produced". At the very beginning of a new project the different departments usually pull checklists from other departments in order to update themselves regarding the technical possibilities, or in other words the "experience will be handed over". At Toyota, engineers do not maintain product history in general but abstract the knowledge gained from previous projects into part specific checklists for coming projects (Sobek et al., 1999). As a result Sobek et al. (1999) explained, "If the design conforms to the checklist, the part will almost certainly meet a certain level of functionality, manufacturability, quality, on so on and discrepancies between the checklists and the design become the focal points of discussions".

Trade-off curves: Trade-off curves, as understood from the literature about Toyota engineering practices, are used to visualise the dependencies between parameters in relation to performance outcomes (Sobek et al., 1999). Whenever possible, Toyota engineers use this technique to be able to intelligently decide among alternatives. As an example, Sobek et al. (1999) described one of Toyota's exhaust system suppliers, who developed several prototype exhaust systems for a car program and tested them on an engine on loan from Toyota. The results gained by extensive testing have been visualised as a gradient between back pressure and noise reduction for different values of a variable. This finally creates the decision-making basis for Toyota to choose the selected design for the program. Trade-off curves are often used within Toyota to "communicate about the sets of possibilities" and to help different departments to understand the "feasible regions" of a technical solution. Or in other words, they create a basis for decisions to be made during the design phase (Sobek et al., 1999).

K4 document: "The K4 is a document that each functional department prepares to work out the main features of their designs" (Ward et al., 1995). "Toyota puts an enormous amount of effort into evaluating the early designs and thinking through all possible engineering and manufacturing issues. Each design is meticulously analysed and countermeasures are developed through study drawings. These are sketches that include possible problems and alternative solutions. When the study-drawing phase is completed, the collective drawings across all engineering departments are put together into a binder called the K4 (shorthand for kozokeikaku)" (Liker, 2004). This paper can be translated to "design structures plan" and is circulated for approval to all affected engineering groups (Sobek et al., 1999).

Design matrices: Within the Toyota organisation the SBCE principle "communicate the sets of possibilities" is enabled by using design matrices. In order to be able to communicate different design solutions in a transparent manner Toyota's engineering groups use standard design matrices. "On one axis are various design alternatives; on the other, key criteria for evaluation. The grid contains the relative performances of alternatives along the criteria." (Sobek et al., 1999) This approach is also used in other companies for concept selection but at Toyota it is used to communicate about alternatives at different phases of a project (Sobek et al., 1999):

Design alternative	Function 1	Function 2	Cost	Space	etc.
X	++	-	+++	-	
Y	-	+++	+	++	
Z	+++	+	-	-	
Excellent: +++ Acceptable : ++ Marginal : + Inacceptable : -					

Figure 2-1 Design matrices adapted from Sobek (1999)

Test-then-design/test-to-failure: A key element of SBCE is to create an information basis which allows decisions to be made based on objective data. When performing extensive prototype testing Toyota engineers apply the technique "test-to-failure (Ijiwara), wherein prototypes are tested to breaking point. The aim of this technique is to learn more about designs and their thresholds, and produce 'limit curves' which capture the results. This technique forms part of the 'test-then-design' method, wherein decisions are made after designs have been tested and factual knowledge (evidence) is provided". (Khan et al., 2011).

Robust design concept (Taguchi method): "Taguchi popularized the concept of robust design, that is, designs that are functional regardless of physical variations such as wear, manufacturing variations, and weather". (Taguchi, 1988; Sobek et al., 1999). Related to SBCE it means to "create designs that work regardless of what the rest of the team decides to do. If one function can create a design that works well with all the possibilities in other function's sets, it can proceed with further development without waiting for additional information from that function" (Sobek et al., 1999). This technique can shorten development time significantly while providing additional advantages like ease of module upgrades and serviceability (Sobek; Ward, 1996).

2.3.5 Point-based engineering approach

Traditional Product Development practice, no matter whether applied in a simultaneous way or not, tends to quickly converge on one design concept (a point in the solution space) and then modify that solution until it meets the technical specifications. This can be an effective approach unless the engineer picks the wrong initial concept. (Sobek et al., 1999). Given that 70-80% of product costs are usually determined during the concept phase of a development process and design changes normally take 30-50% of the total project costs, sometimes even 70% (Ehrlenspiel et al., 2005; Lindemann et al., 1998; Lenders, 2009), a Point-Based approach to Product Development can objectively be rated as critical. “Even with a great deal of concurrency in the design process the basic process remains the same: The design team is iterating on one solution” (Sobek et al., 1999). And there is no theoretical guarantee that this process will ever converge, the team simply stops work when it runs out of time and very often ends up with a compromised product in terms of cost, quality and requirements fulfilment (Sobek; Ward, 1996). Effective, truly concurrent design requires a change from this point-based paradigm. Moving iteratively from point to point in the design space (communicating a single, specific solution and subsequent modifications) means that any decision made by one member of the design team may invalidate previous decisions. This creates a powerful incentive to delay acting on communication from other groups and to sequence decisions, thus destroying parallelism (Liker et al., 1996).

2.3.6 Set-based versus point-based

Figure 2-2 illustrates an iterative point-based approach compared to the set-based approach:

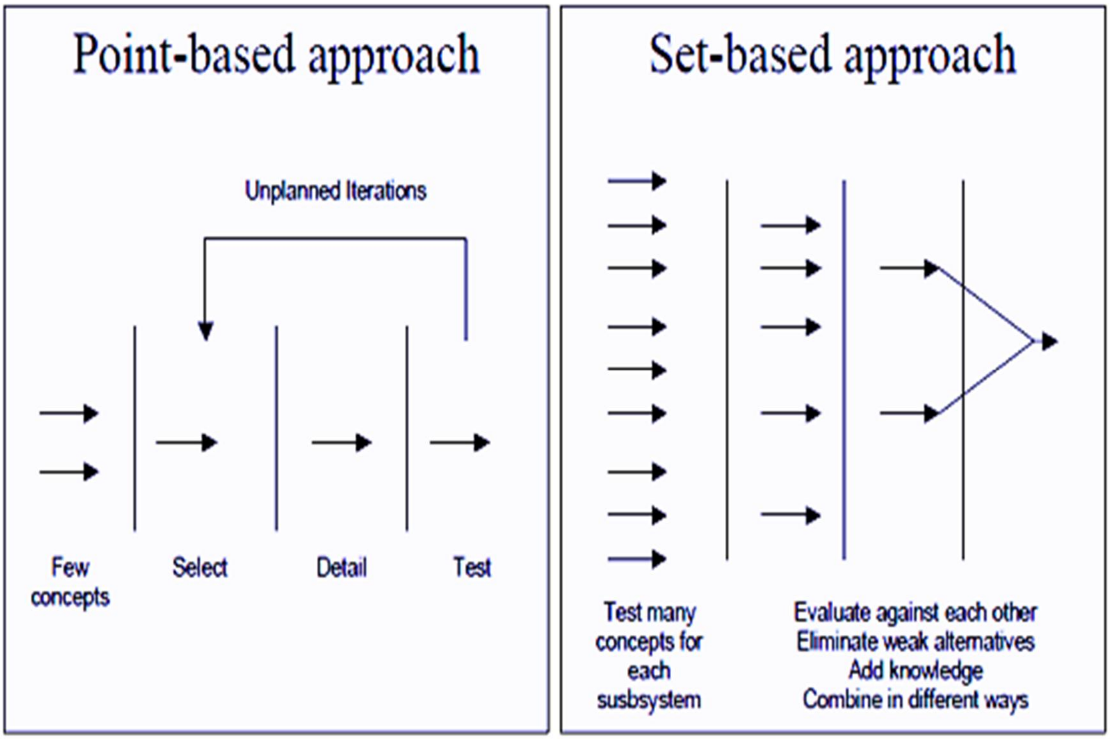

Figure 2-2 Engineering approaches adapted from Kennedy (2008)

Based on the literature review conducted as well as the author's personal engineering management experience it can be concluded that both approaches, point-based and set-based, can be successful depending on the actual design task and the related circumstances. As Terwiesch et al. (1997) already suggested, an iterative strategy may be optimal when iteration or feedback cycles are fast, the cost of rework is low, and the quality of the initial starting point ("first guess") is high". In the same context Liker et al. (1996) explained that "many companies used a sequential model in which product designers did their best to meet their objectives, and then let manufacturing react. This works well as long as the interdependence remained low across components or between the product design characteristics and the manufacturing process characteristics, or when the product was mature and well understood through years of redesign and production". The probability of finding the optimal solution for a real new product is much higher with a set-based approach than in the point-based approach.

2.4 Challenges for implementation of SBCE

The success of SBCE at Toyota is based on the decision and negotiation manner of their engineers which has grown over decades (Smith, 2007). Even at Toyota there is no formal process of how to apply SBCE. It is more a philosophy than a defined process (Ward et al. 1995; Sobek et al., 1999). “The principles of SBCE are not steps, prescriptions, or recipes. Rather, Toyota Chief Engineers apply the principles to each project differently. Ward et al. (1995) concluded that the methodologies need to be applied and validated in different companies and that further work is required to define the parameters of this research area. He advised to avoid crash programs. Rather, companies should develop specific techniques and take a more formal approach to gain this new competitive edge, which is also the intention and motivation of this research. In addition, a set-based approach to development processes is more complex than a point-based approach and requires higher skill sets and more experience from the engineers (Ward, 1995). In this context Liker et al. (1996) referred to one Toyota Engineering General Manager who stated that most suppliers like hard specifications better then parameter ranges or ambiguous targets, because they did not have the required skills to handle it. “It may be that set-based methods are confusing and difficult for suppliers, but lead to breakthroughs, superior designs, better integration of the overall product, and ultimately competitive advantage”. In addition to the above mentioned reasons the manner of today’s bidding and contract awarding makes it quite difficult not to define a final product concept already in the offer stage of a project. Therefore this research will focus on pilot projects without an existing customer behind to test and validate the methods.

2.5 Socio-technical aspects for SBCE-implementation

At first glance the consideration of multiple alternatives appears as extra work and the stakeholders of the development project are usually difficult to persuade. Naturally, people desire a high degree of certitude which supports an early definition of a concept. A continuous containment of alternative solutions requires more effort and passion (Lenders, 2009). Furthermore, Ringen (2011) found during his research into how enablers for Lean Product Development motivates engineers that performance will be maximised when goals are specific and concrete. Additionally, it can be considered as very challenging to persuade other departments, such as Sales and Marketing for instance, not to have "something to show" very early in the process in order to see the project as on the right track (Lenders, 2009).

Turner (2004) found that many companies are still unaware of the concept of SBCE and have many reservations against implementing it into the design cycle. These reservations include:

- High cost due to high number of prototypes
- Contradicts trends towards Right First Time
- Timescales do not allow for multiple designs

The following figure provides an overview of the potential resistance to implementing SBCE in a company. These reservations should be addressed when introducing SBCE techniques to a company:

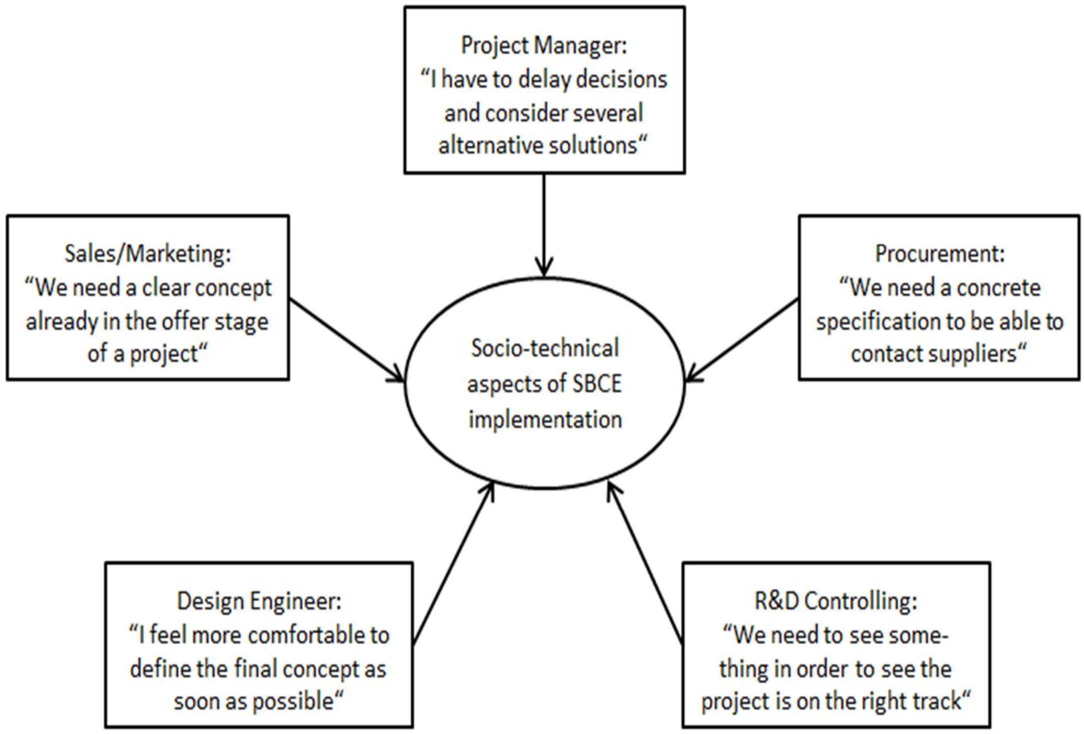

Figure 2-3 Socio-technical aspects adapted from Lenders (2009)

2.6 Applications of SBCE outside Toyota

“The research provides minimal evidence of effectiveness of applying Toyota PD outside of Toyota. One reason for this is that the area of research is fairly new, and has been overshadowed by lean manufacturing and lean enterprise research” (Khan et al., 2011). Lenders (2009) found during his doctoral dissertation at RWTH Aachen that Project Managers intuitively tend to a highly alternative oriented approach particularly in projects with a high strategic relevance and unknown environment with regard to the market and technology. As an example he described the development of the Mercedes W201 in the late 1970s. The oil crises in the middle of the seventies demanded the development of a new generation of fuel-efficient cars with gas engines. The Daimler Benz AG has concluded, in order to keep their market share, to scale down their product range and initiated the development of a new car generation called "compact class" with the following main goals: fuel-efficiency, weight reduction (280Kg), easier maintainability and smaller in size (minus 30cm in length and 10 cm in width). According to Mercedes-Benz (www.baureihe201.de, 2007); Lenders, 2009) they built as many as 53 prototypes to explore the ground concept on full vehicle level. After committing to the ground concept they started extensive research especially on the rear suspension system and they physically validated 8 different base concepts in 77 different alternative solutions (www.spiegel.de, 2007; Lenders, 2009). This tremendous effort resulted in a breakthrough rear suspension design with regard to design envelope, weight and driving characteristics. Mercedes-Benz has sold 1.8 billion W201 cars.

In earlier times Al-Ashaab et al. (2013) came up with a case study from the aerospace industry. The existing development process of the collaborating company has been enhanced by the integration of set-based concurrent engineering principles, including their associated tools and activities. The transformed product development process model was trialed in an industrial project of a helicopter engine, tested to evaluate its value in enhancing the innovation level and reducing the risks. The feedback from the involved PD stakeholders highlighted the strong possibilities of improvement in the design process in terms of available alternative solutions, level of innovation and decreased risk of rework (Al-Ashaab et al., 2013).

2.7 SBCE baseline model of the LeanPPD project

As part of the collaborative European research project titled "Lean Product and Process Development" (LeanPPD), which is supported by the European Commission for Research and managed from Cranfield University, UK, an SBCE baseline model has been developed.

Through an extensive literature review the main principles of SBCE have been identified and Khan et al. (2011) defined a newly described set-based concurrent engineering process, which they believe will address some of the key challenges faced by engineering companies in the 21st century (Khan et al., 2011). Their findings are illustrated in Figures 2-4 and 2-5, followed by a brief description of the key phases of the process:

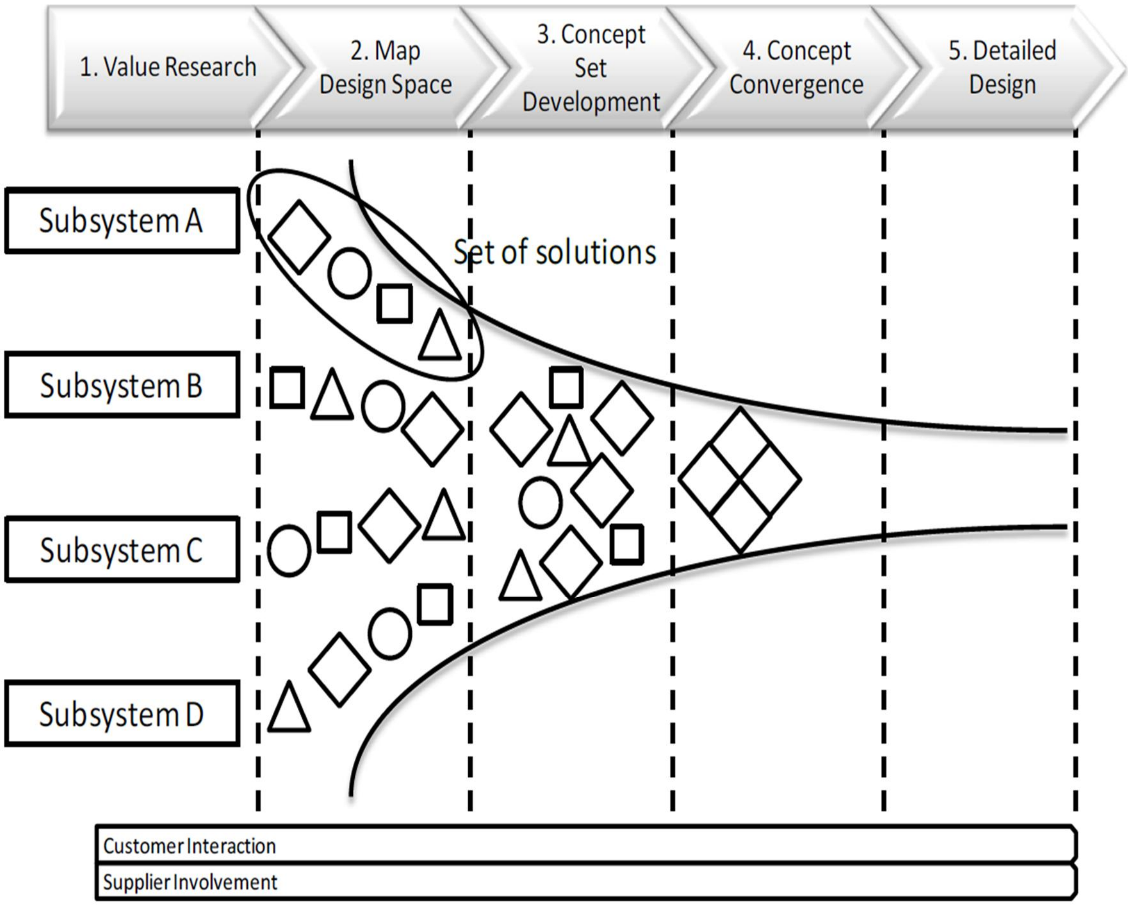

Figure 2-4 SBCE baseline model (Khan et al., 2011)

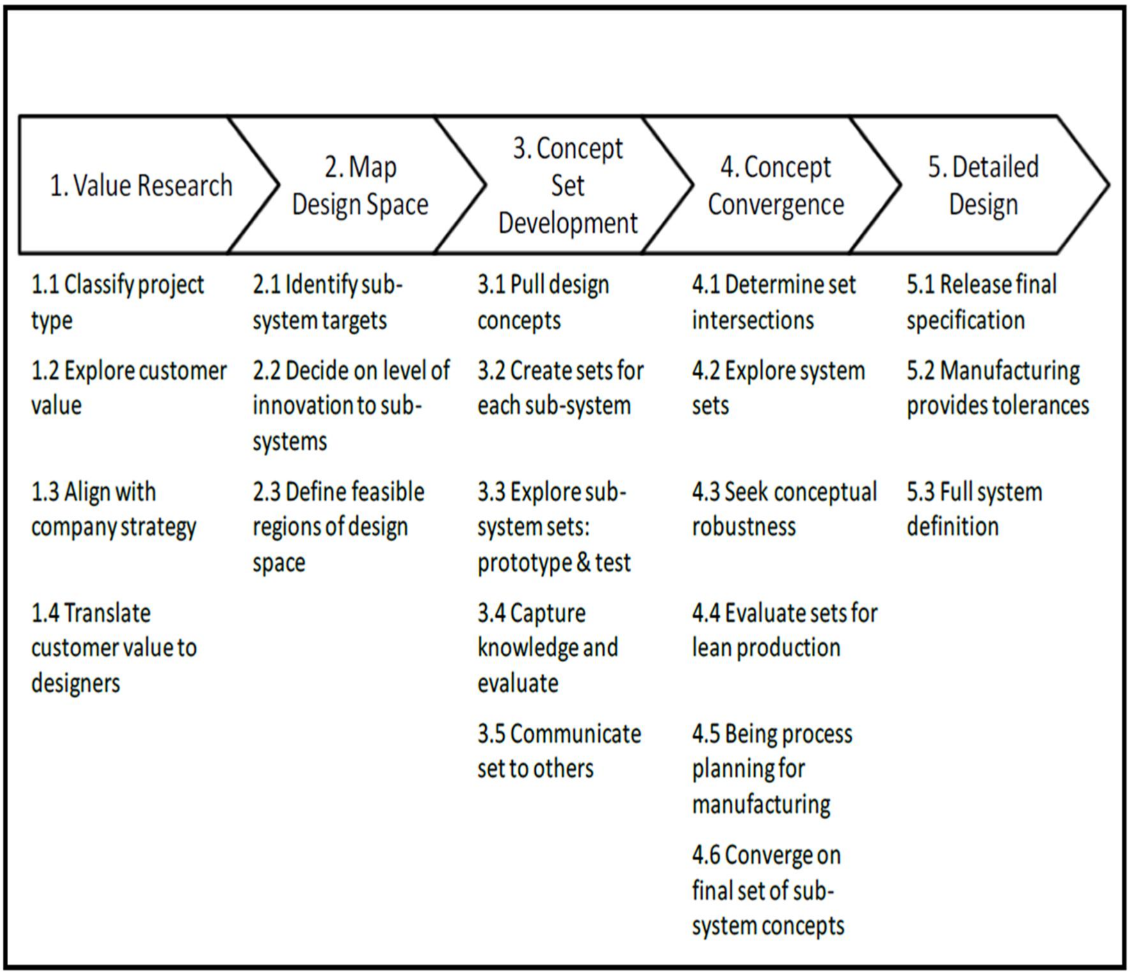

Figure 2-5 SBCE baseline model (Khan et al., 2011)

”Customers and suppliers are considered to be involved throughout the product development process. During the first phase (value research), the initial product concept definition is developed based on a strategic and thorough internalisation and analysis of value. In phase 2 (map the design space), design participants or sub-system teams define the scope of the design work required as well as the feasible design options/regions. In the third phase (concept set development), each participant or sub-system team develops and tests a set of possible conceptual sub-system design solutions; based on the knowledge produced in this phase some weak alternatives will be eliminated. In phase 4 (concept convergence), sub-system intersections are explored and integrated systems are tested; based on the knowledge produced in this phase the weaker system alternatives will be purged allowing a final optimum product design solution to enter phase 5: detailed design” (Khan et al., 2011).

3 RESEARCH OUTLINE

3.1 Research gap

The main research gap is the lack of a clear structured SBCE model with well-defined process steps, activities and tools, as SBCE is usually just presented as a set of generic descriptive principles (Al-Ashaab et al., 2013). The second challenge is a missing guideline or step-by-step methodology of how to integrate or embed set-based process steps into an existing product development process landscape. “There is a need for a step-by-step guide to enable designers to progress with sets of solutions throughout the product development process, and what tools to use for each activity” (Al-Ashaab et al., 2013). In addition, and this is what most likely makes the product development personnel reluctant to implement SBCE, is the limited number and variety of real case studies conducted in the industry (Khan et al., 2011).

3.2 Research methodology

3.2.1 Research methodology structure

The underlying research methodology, illustrated in Figure 3-1, has been created in order to present a general overview of this research and to guide the author through the work to be performed.

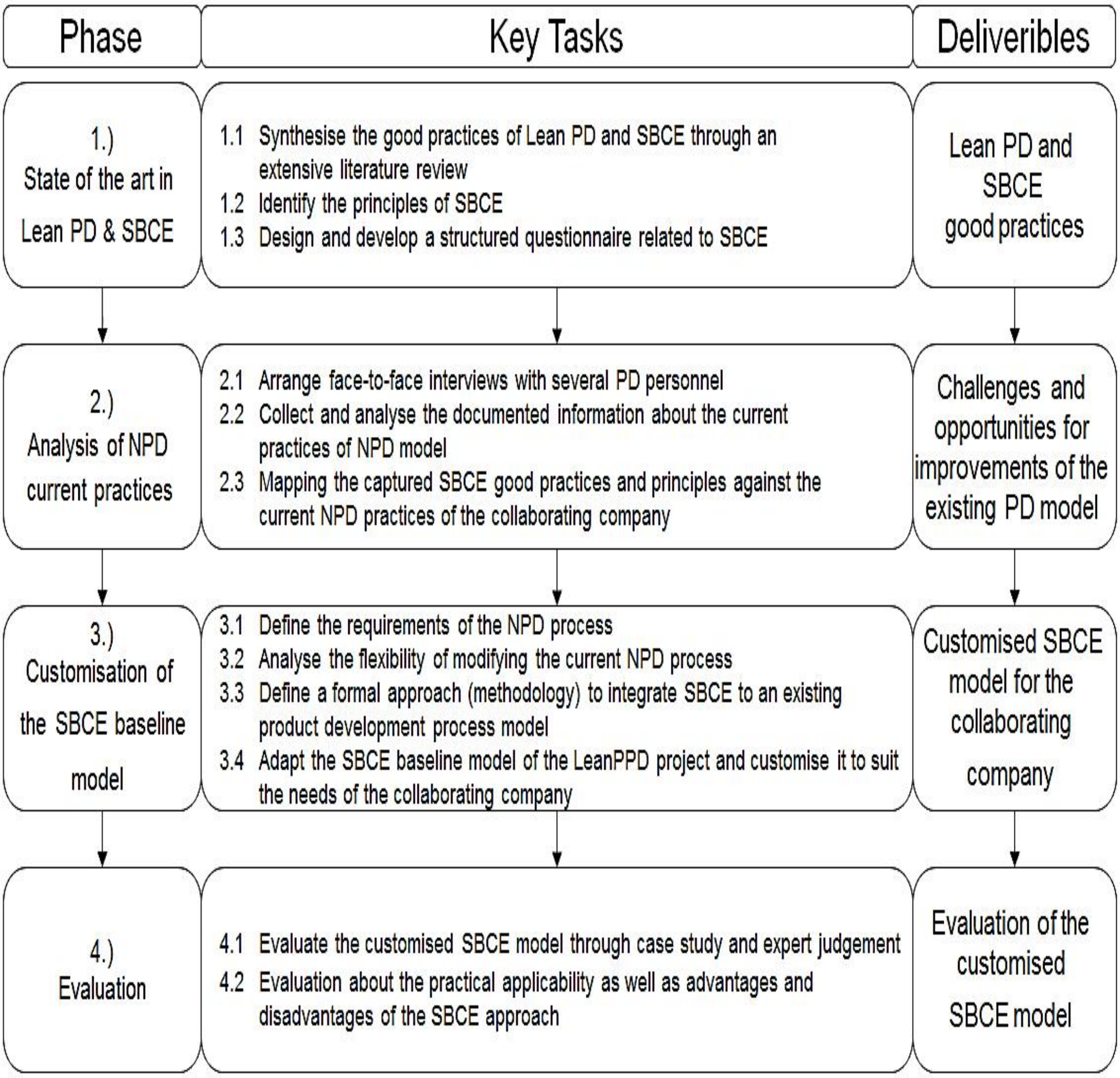

Figure 3-1 Research methodology

3.2.2 Research methodology phases

The research methodology of this research study is divided into 4 main phases:

Phase 1: State of the art Lean PD & SBCE

The main purpose of phase 1, presented in Chapter 2, is to create a thorough understanding of set-based concurrent engineering in the context of lean product development accomplished by an extensive literature review. The advantages of SBCE, the challenges for the implementation, the enablers which support its application as well as the principles of the SBCE baseline model will be identified.

Phase 2: Analysis of NPD current practices

Based on the knowledge gained in phase 1 a questionnaire related to SBCE has been developed. The questionnaire development will be detailed in Chapter 4. Guided by that questionnaire, face-to-face interviews have been conducted with participants from different management levels and functions within the company. The collected data will be analysed in order to map the current practices in the company against the SBCE good practices and principles with the goal of extracting the challenges and opportunities for improving the existing development process.

Phase 3: Customisation of the SBCE baseline model

Based on the challenges and opportunities worked out in phase 2 the detailed requirements for the improved new product development process will be defined. After analysing the possibilities of improving the process the SBCE baseline model will be adapted accordingly. Before starting the evaluation process initial feedback from the key stakeholders will be obtained in order to gain commitment and acceptance for this new approach.

Phase 4: Evaluation

A case study will be defined in order to apply the customised new product development process. This evaluation will give an indication of whether and how the new SBCE approach benefits the efficiency and effectiveness of the new product development. A final evaluation will be given regarding the extent to which this new approach is practically applicable to the new product development system of the company.

4 FIELD STUDY IN THE COLLABORATING COMPANY

4.1 Questionnaire development

Based on the findings of the literature review a questionnaire has been developed which is structured corresponding to the different phases of the SBCE baseline model. The objective of this questionnaire was to analyse the current product development practices within the collaborating company in relation to the set-based concurrent engineering (SBCE) principles. It has been taken into consideration that the questionnaire should be also applicable to other companies. Therefore it has been developed with a generic character without being specific to a particular company or industry sector.

The final version of the questionnaire, consisting of 26 questions in total, is provided in Appendix A.

4.2 Interviewee details

The chosen candidates came from various functions such as mechanical engineering, electrical engineering and software engineering as well as from different management and engineering levels, which was important to provide an overall picture of the current practice. Guided by this developed questionnaire 21 interviews in the company have been conducted. Each interview was held face-to-face in order to enable the researcher to understand and interpret personal viewpoints and possible interests or reservations. The length of the interviews ranged from 60-120 minutes.

A detailed overview of the 21 interviewees is given in Table 4-1:

Interviewee Details			
No	Role in organisation	Years in current Role	Level of interviewee
1	Manager Engineering & Design	1.5	Middle Management
2	Design Engineer	4	Engineer
3	Design Engineer	2	Engineer
4	Design Engineer	5.5	Engineer
5	Design Engineer	4	Engineer
6	Design Engineer	4	Engineer
7	Team Leader Soft- and Hardware	5	Middle Management
8	Software / Hardware Engineer	7.5	Engineer
9	Team leader Electrical Engineering	4.5	Middle Management
10	Electrical Engineer	2	Engineer
11	Design Engineer	3	Engineer
12	Project Manager Customising	3.5	Engineer
13	Product Manager	1	Middle Management
14	Manager Engineering & Design	2	Middle Management
15	Project Team Leader Customising	4	Middle Management
16	Head of Project Management	8	Senior Management
17	Head of Project Management	5	Senior Management
18	Project Team Leader Customising	6	Middle Management
19	Design Engineer	3	Engineer
20	System Engineer	4	Engineer
21	Head of Quality Management	3	Senior Management
Average:		3.9	

Table 4-1 Interviewee details

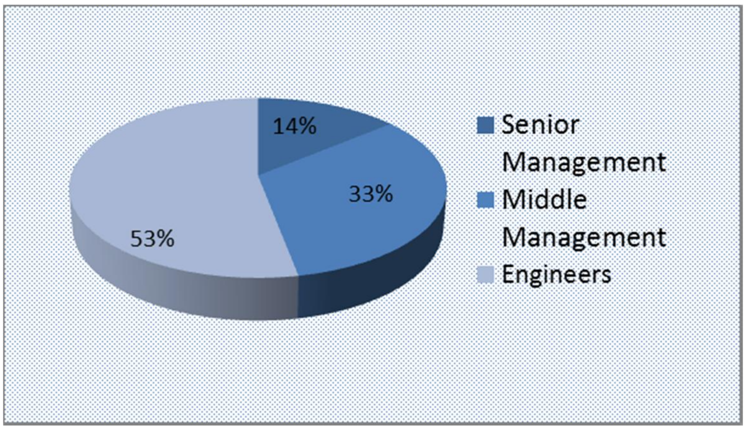

Figure 4-1 Interviewee details

4.3 Main findings from the data analysis

In the following Chapter the author outlines the key findings from the data analyses of the questionnaire results:

Question: How are typical development projects running in the company?

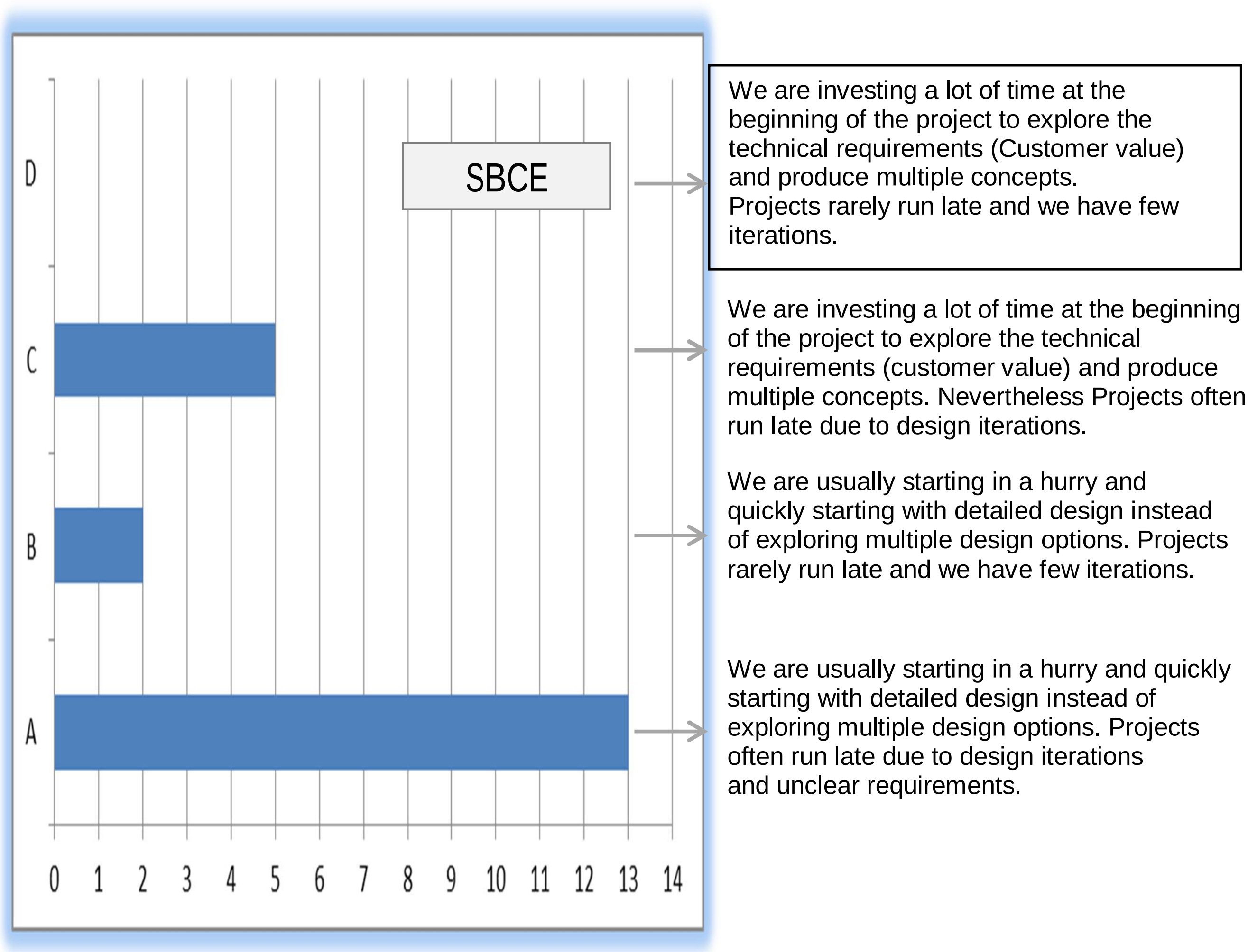

Figure 4-2 Typical projects in the company

Figure 4-2 illustrates the candidates' evaluation of how typical projects in the company are running from their own perspective. Approximately 62% of the interviewees selected option A, which gives a clear indication that engineers usually do not explore multiple design options but tend to start too early with detailed design, which in turn results in design iterations and failed time schedules.

Question: How would you describe your current approach in concept selection for a new product?

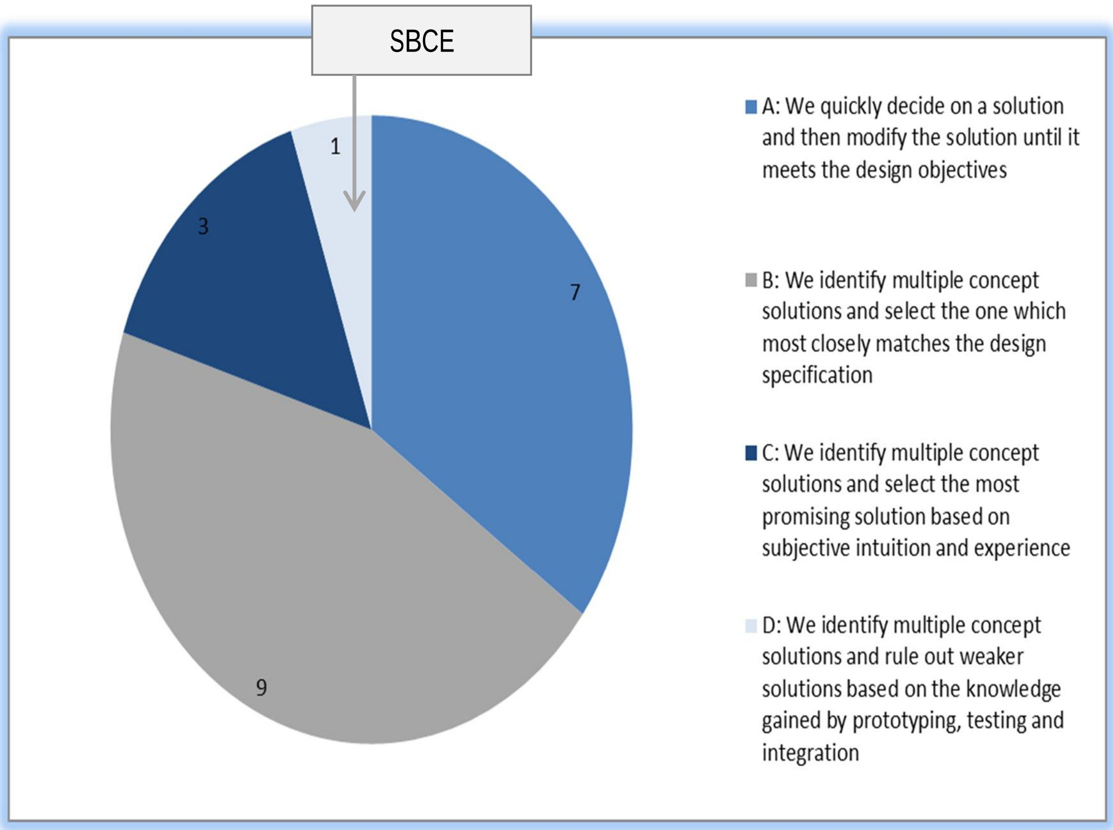

Figure 4-3 Current approach in concept selection

The feedback from the interviewees in relation to the current approach of concept selection is represented in Figure 4-3. The result was that engineers tended to quickly decide on a solution which most closely matches the design specification instead of exploring and testing multiple concepts until the most optimal solution evolves from the set of possibilities.

Question: Do you usually produce multiple design options during a development project?

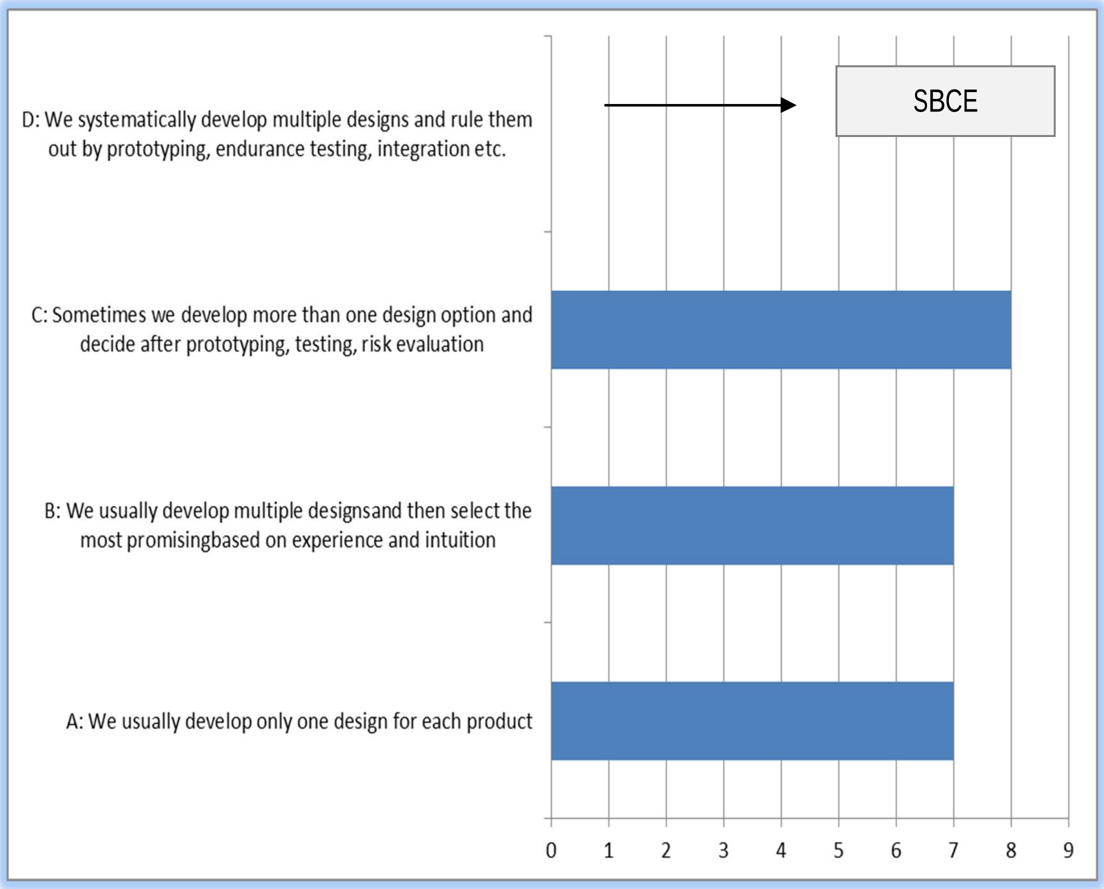

Figure 4-4 Current approach in concept selection

None of the engineers selected answer D, the set-based concurrent engineering approach, which means to systematically develop multiple designs and rule out weaker solutions out based of facts gained from prototyping or endurance testing.

Question: To what degree do you usually iterate the design before you meet the customer demands?

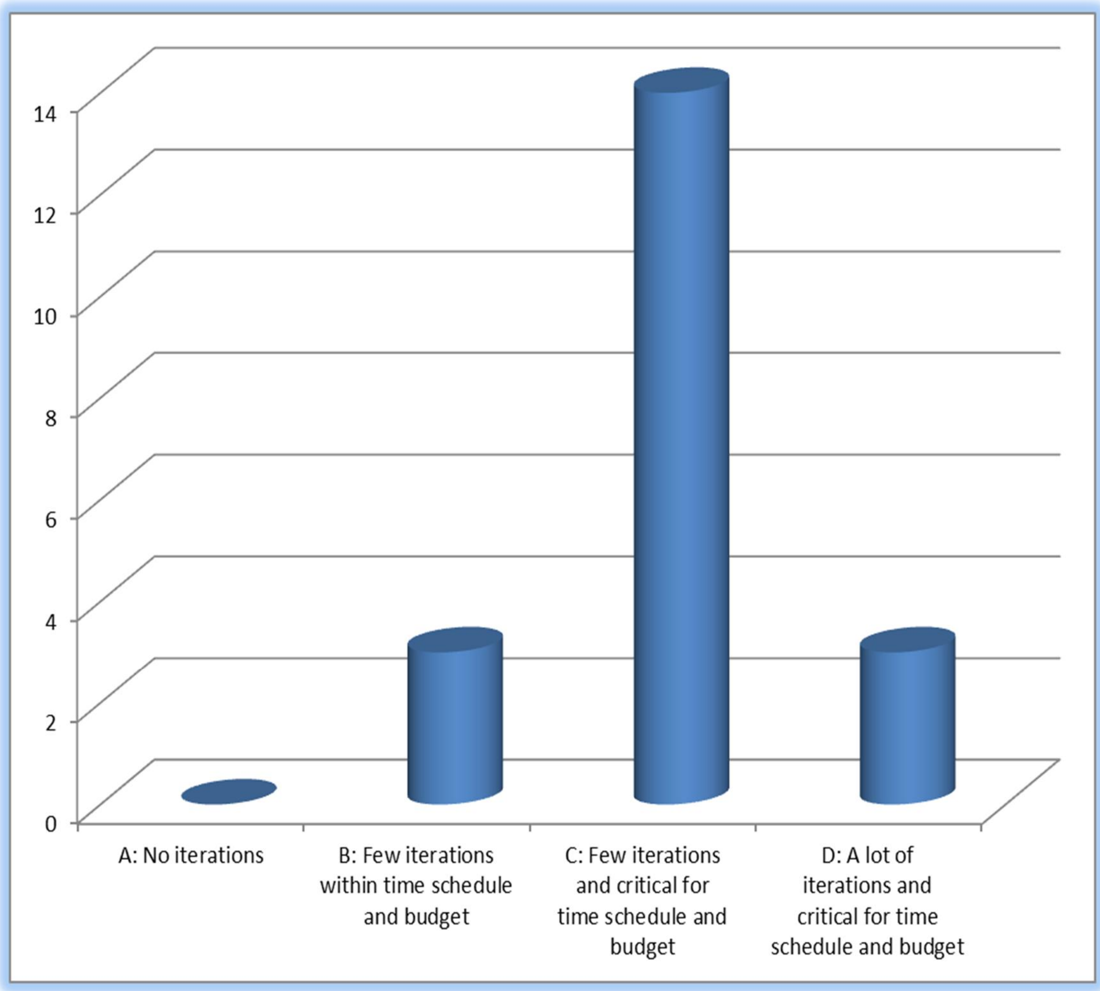

Figure 4-5 Design iterations

Figure 4-5 shows that in the daily product development practice design iterations are quite usual. Those iterations are mostly considered as critical in terms of cost targets and time schedules.

Question: Which of the following aspects do you think need more attention within the current product development model?

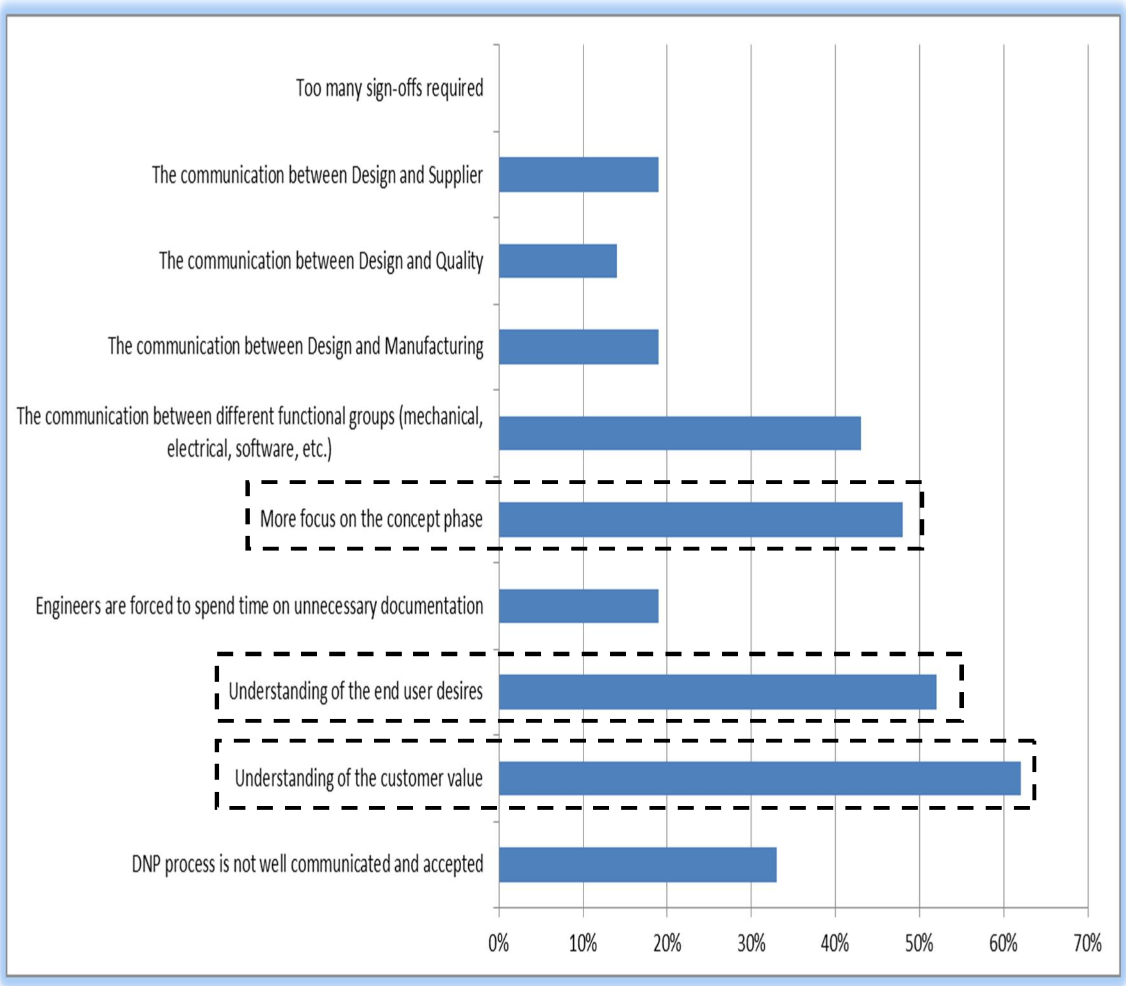

Figure 4-6 Important aspects for improvement

The top 3 selected options are marked in Figure 4-6. The candidates already realized that more focus on the concept phase in combination with a thorough understanding of customer values and end user demands would probably improve the performance.

Question: How do you manage the interface between design and manufacturing/production?

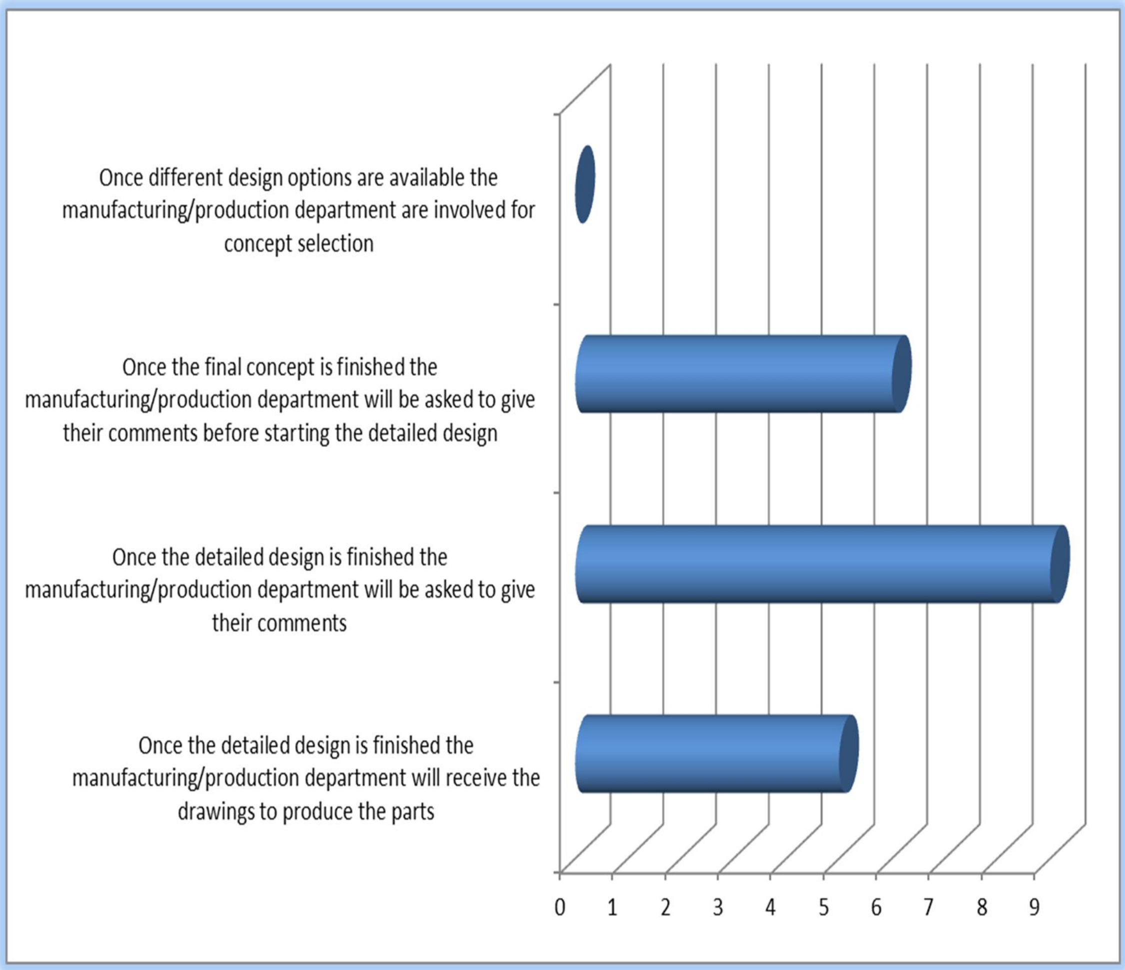

Figure 4-7 Involvement of manufacturing

Figure 4-7 shows that involvement of manufacturing emerges too late in the process in comparison with the requirements of SBCE. None of the interviewees considers manufacturing to be involved for concept selection.

The complete questionnaire developed and applied for this field study can be found in Appendix A.

4.4 Interim conclusions

The conducted field study in the company resulted in a very clear overall picture of the current product development approach in relation to set-based concurrent engineering methodologies. Current practice shows very little formal consideration of SBCE tools and techniques, less focus on the concept phase as well as undervalued customer and end user´s demands. A simultaneous and systematic exploration of multiple solutions for a product by different design teams or functions is quite unusual. Furthermore, design iterations and failed cost targets and time schedules are considered to be serious problems. All in all, the outcome of the field study indicates a lot of potential areas for improvement and the need for formal implementation of certain SBCE tools and techniques to be embedded in the current PD model.

The responses from the different participants showed mixed results. Some engineers showed considerable interest in the SBCE approach and offered their support during the pilot project as well as for a possible implementation phase of the validated customised SBCE model later on. Beside this positive feedback some candidates explained their reservations towards such a multi-concept approach due to common time pressure, especially at the beginning of a project. In former projects it was unfortunately necessary to show the final concept very early in the project in order to convince potential customers or internal stakeholders, such as in Sales & Marketing.

4.5 Requirements for the process model transformation

This section summarizes the key requirements for the process model transformation extracted from the data analysis of the field study. The results show several opportunities for improvement. The most important areas of improvement have been identified which could further enforce the current practice towards a more innovative, robust and customer-oriented way of product development. The key requirements are the following:

- Innovation classification to be established at the beginning of the project
- Enhancing of customer value exploration with the goal of establishing a more customer-oriented way of product development
- Conscious translation of the explored customer value to the stakeholder of the development process
- Implementation of an “multi-concept”-approach
- Establish an approach in which weak alternatives will be ruled out based only on data instead of based on intuition or experience
- Create an approach in which different functions create sets of possible solutions, and communicate them among the design teams in order to understand interdependencies and intersections of possible solutions with the goal of finding the optimum
- Sensitise engineers to consider “noise factors” during the design
- Sensitise engineers for early supplier and manufacturing involvement

The aforementioned requirements will be considered during the process model transformation in the following chapter.

5 Transformation of the current Product Development into SBCE

5.1 Introduction

As described in the previous chapters, SBCE appears to be a very promising approach for successful new product development. Nevertheless, the existing literature is still lacking a clear and structured SBCE model including a guideline for how to implement it in practice. SBCE is rather described as a set of generic descriptive principles (Al-Ashaab et al., 2013). “There is a need for a step-by-step guide to enable designers to progress with sets of solutions throughout the product development process, and what tools to use for each activity” (Al-Ashaab et al., 2013). This chapter refers to tasks 3.3 and 3.4 of the research methodology and aims at defining a formal approach to integrating SBCE into an existing development process within the collaborating company.

5.2 Generic transformation methodology

In order to create a transformation guideline, that could also be adopted and applied from other companies in different industry sectors, a generic step-by-step approach has been defined by the author. The whole transformation has been segmented in 6 subtasks. Table 5-1 gives an overview of the steps to be applied including an activity description and the intended outcome of each step:

STEP	TRANSFORMATION ACTIVITIES	OUTCOME
1	Summarize key process steps from the existing development process of the company onto one page similar to the SBCE baseline model	Current process model overview
2	Apply ‘quality gate approach“ of the existing product development process of the company to the SBCE baseline model process layout	General setup of the transformed SBCE baseline model
3	"Translate" the wording from SBCE baseline model to the existing Matrix organization of the company	Wording harmonization and clarification
4	Map the SBCE baseline model process steps against the current practice in order to understand the potential areas of improvement	Requirement matrix
5	Define the top level process layout by embedding SBCE baseline process steps in accordance with the requirement matrix	Top level process landscape
6	Detail out each phase of the new transformed process model steps by defining activities and tools to be applied in the relative steps	Customized SBCE baseline model

Table 5-1 Transformation methodology

5.3 Step 1: Summarizing of existing process model

Product development processes are usually quite complex and the respective process description and illustration in relation to the specific tasks and activities are often voluminous and widely scattered (Al-Ashaab et al., 2013). In order to be able to achieve an overview of the existing development process and to identify potential weak points, the transformation process will start with an extraction and summary. The goal is to accomplish a process outline similar to the one from the SBCE baseline model shown in Figure 5-1. In the case of the PD process model being currently presented on several pages it must be summarized into a one page overview. This will allow the SBCE baseline model (Figure 5-1) and the existing development process model to be laid on top of each other and to identify the gaps and potential areas for improvements:

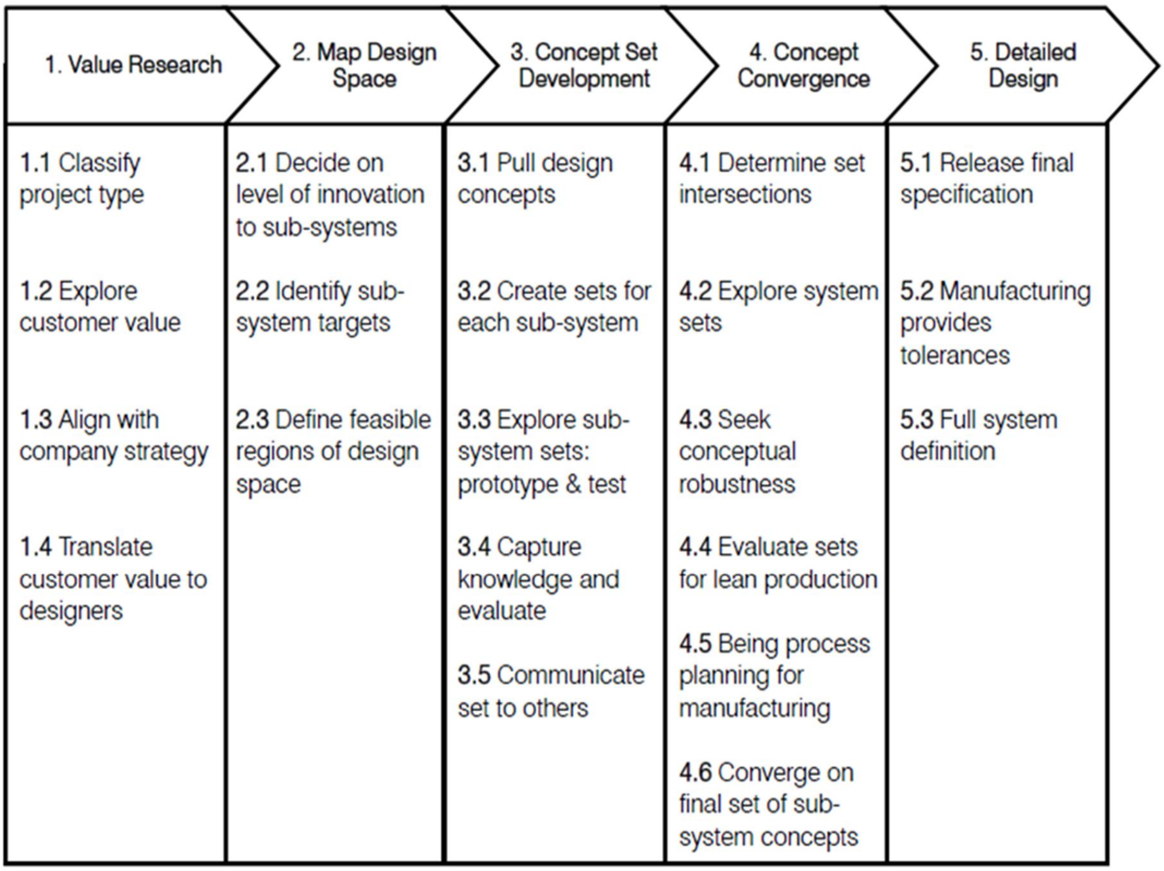

Figure 5-1 SBCE baseline model the LeanPPD project (Khan et al., 2011)

Within this research the existing product development process of the collaborating company, a four pages long swim lane diagram, has been summarized onto one page. Figure 5-2 provides a few examples of how the different and partly scattered process steps from the current process model have been rearranged in order to fit into a one page overview table:

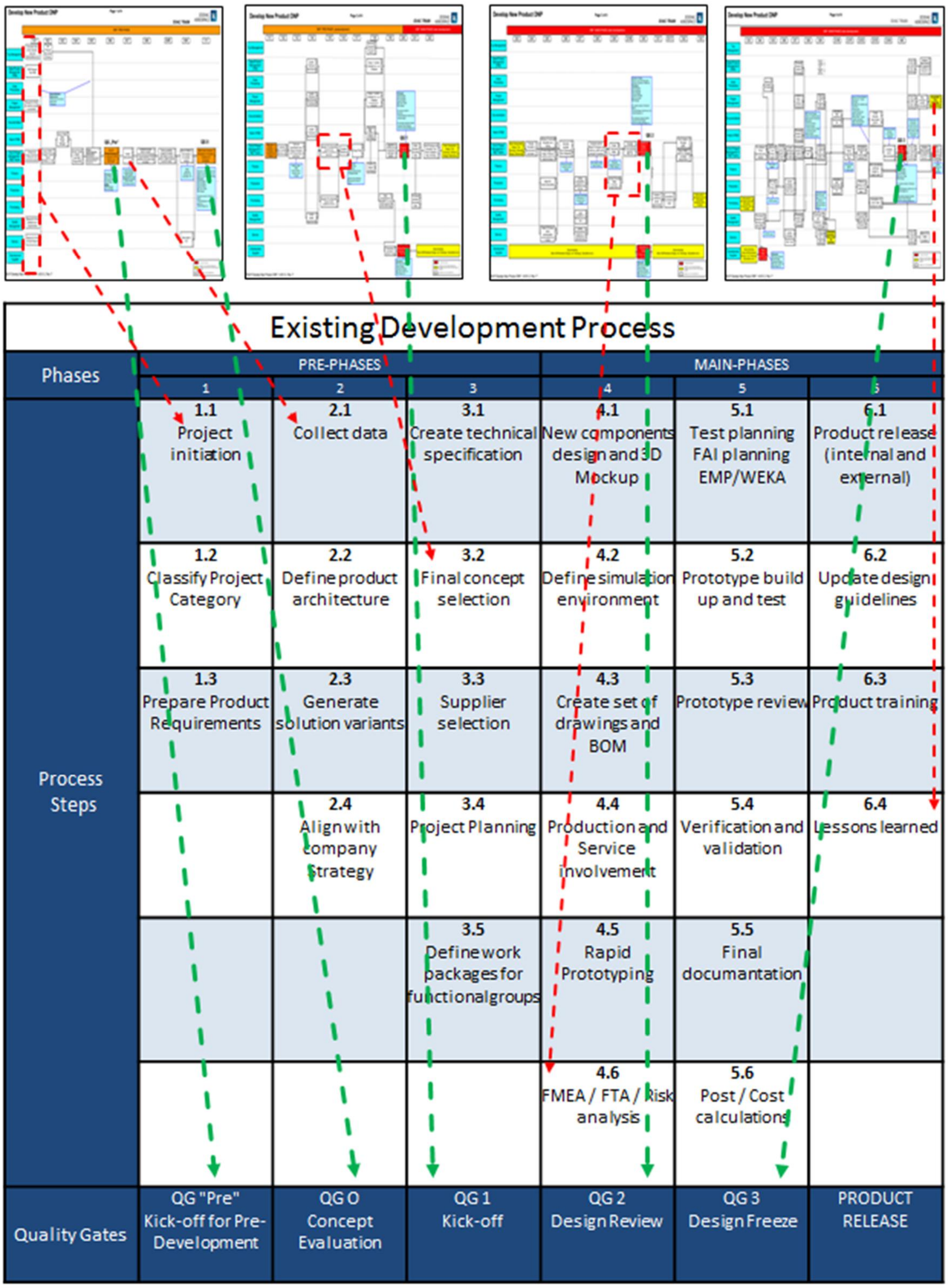

Figure 5-2 Existing process model summary

5.4 Step 2: General process set-up definition

Based on the findings of the field study, it is recommended to keep the existing quality gates, as far as possible, within this case study. Each phase of the new process development process will conclude with a quality gate, which is considered to be an effective tool to align the status and common understanding of the project. In addition, the general lay-out of the SBCE baseline model with its 5 phases will be retained. This approach has been chosen in order to achieve following two main advantages:

- The stakeholders of the process can continue to work with the quality gates (i.e. process milestones or toll gates) they are used to.

- The set-based approach of the SBCE baseline model structure can be introduced as it is.

In addition, the wording of the SBCE baseline model phases have been slightly adapted in order to be more self-explanatory and reflecting the activities that will be conducted during each phase. For instance “Value Research” (Phase 1) has been renamed “Product Value and Concept”.

Figure 5-3 provides an overview of the general set-up of the transformed SBCE baseline model where phases 1-5 have been adapted from the SBCE baseline model and the bottom quality gates have been taken from the existing PD model of the collaborating company as they are considered to be effective according to the results of the field study. However, the quality gates have been newly allocated to the 5 phases of the SBCE baseline model:

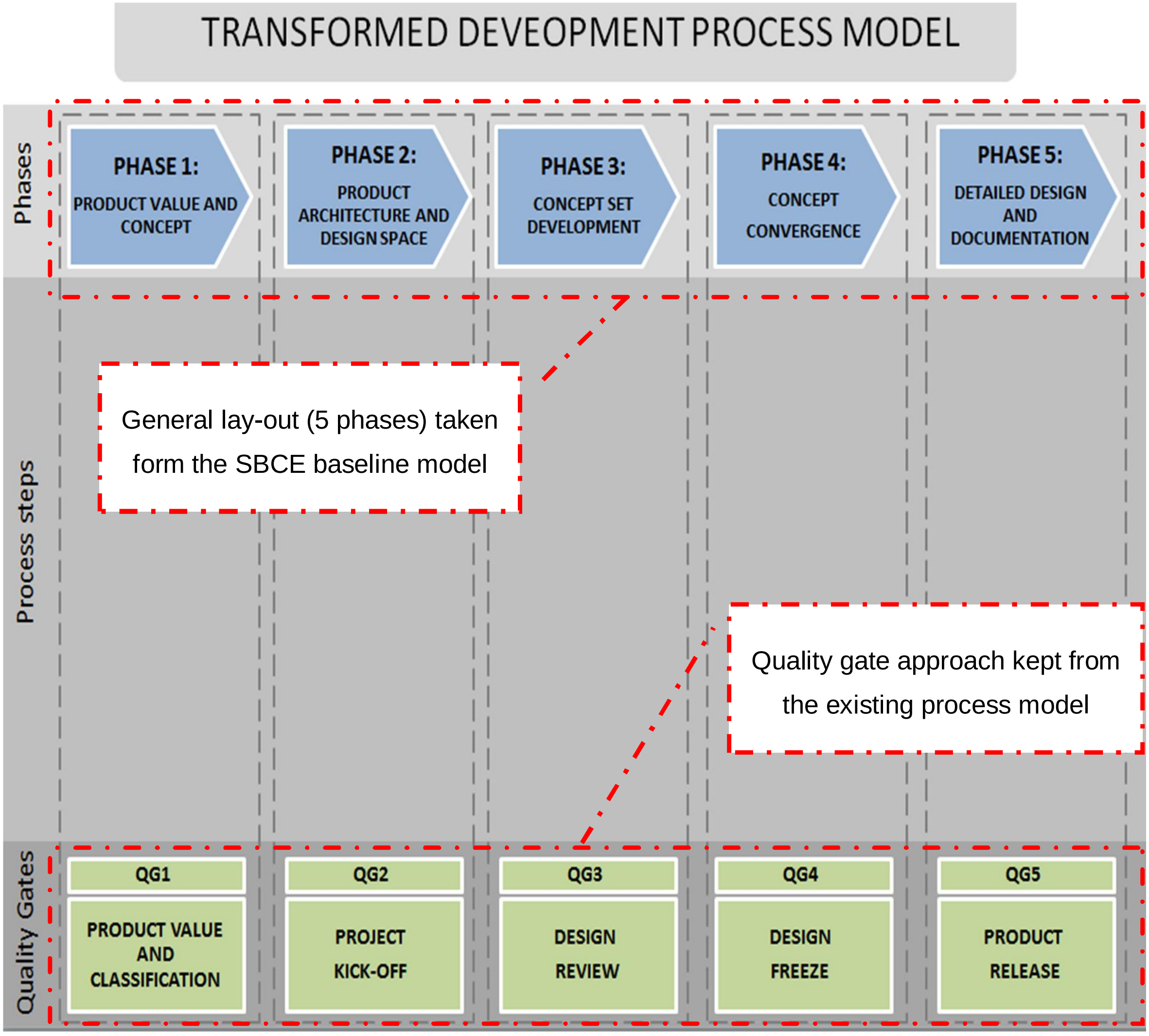

Figure 5-3 General process layout definition

5.5 Step 3: Wording harmonization and clarification

Many companies are still unaware of the concept of SBCE and have many reservations for implementing it into their product development activities (Turner 2004). The continuous consideration of multiple alternatives appears as extra work and the stakeholders of the development project are usually difficult to persuade. As already described in Section 2.5 several reservations should be addressed whilst introducing SBCE techniques to a company. Hence, it makes sense to consider company specific givens, as for example the internal wording which is characterized by the respective product structure, and harmonize it with the SBCE approach.

This would allow the stakeholders of development processes to keep their linguistic usage based on the organizational structure of the company. Step 3 of the transformation methodology is therefore defined as a harmonization of the wording from the SBCE baseline model with the existing organization of the company.

As a first task within this step the organizational engineering structure of the company has been investigated. The current engineering structure is a typical matrix organization (Figure 5-4). In a matrix project organization two competence and responsibility systems are combined with each other. The vertically directed functional responsibilities are overlaid by the horizontal project responsibility. This means that the project managers have no direct authority over their cross-functional team members. The functional expert teams or departments such as electrical engineering, mechanical engineering or software engineering are headed by team leaders or managers. While the Project Manager is responsible for the complete product the functional experts are responsible for their area of the product based on the functional discipline.

Figure 5-4 gives an overview of a typical matrix organization as practiced in the company:

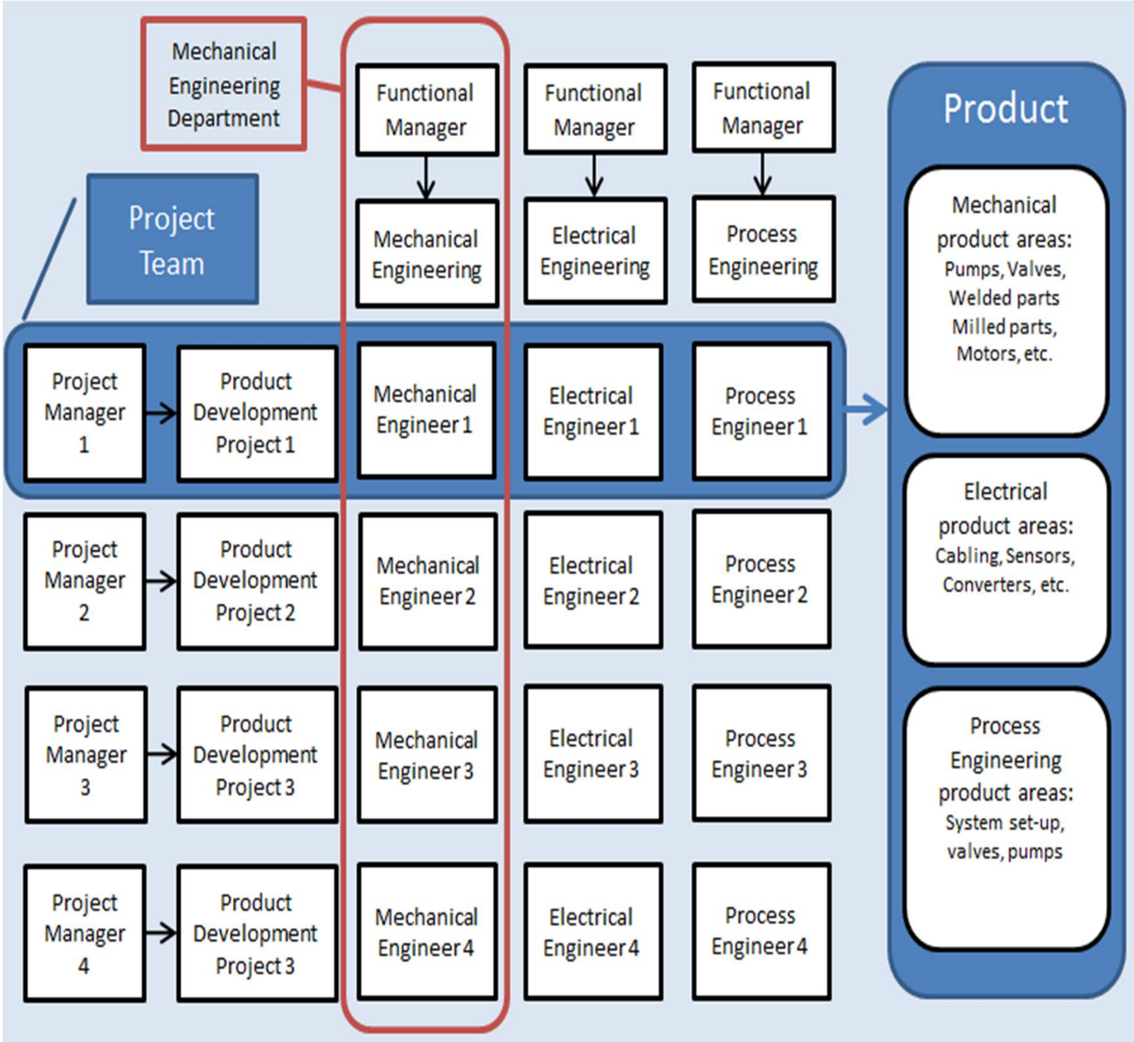

Figure 5-4 Typical matrix engineering structure

Taking into consideration the given form of organization and engineering structure the following translation definition has been developed:

SBCE baseline model activities		Applicable activities in consideration of the engineering structure of the collaborating company
2.1	Identify **sub-system** targets	Identify targets for each functional group like mechanical, electrical or software engineering for their relative **product area**
2.2	Decide on the level of innovation to **sub-systems**	Decide on the level of innovation the different functional group shall implement to their **product area**
3.2	Create sets for each **sub-system**	Each functional group creates possible solutions (sets) for their proportion of the product (**product area**)
3.3	Explore sub-system sets: Prototype & test	Each functional group explores their relative sets by prototype testing, simulation and expert judgment
3.5	Communicate sets to others	Feasible technical solutions of different functional groups shall be communicated between them
4.1	Determine set intersection	Compatible **product configurations** will defined based on possible solutions for different **product areas** developed by functional groups
4.2	Explore **system sets**	Potential **product configurations** shall be simulated, prototyped and tested for cost, quality and performance
4.4	Evaluate sets for lean production	Evaluate product configuration for lean production
4.6	Converge on final set of sub-system concepts	Converge on a final **product**

Table 5-2 Wording harmonization and clarification

While the SBCE baseline model is talking about “sub-systems” and “systems” those terms have been renamed as “product area” and “product”. However, the bottom-up product development methodology from the SBCE baseline model has been transferred into the product development environment of the company. The theory of SBCE is shown in Figure 5-5 A, where the product development is starting on sub-system level. This has been changed to B, where the product for example has been divided into its mechanical or electrical part. As shown in C, the SBCE baseline model starts with the set-development on sub-system level, whereas the transformed process model is talking about set development on product area level, based on the different functional groups involved (D). Figure 5-5explains this approach where possible product area solutions will be designed and explored until a final product configuration converges.

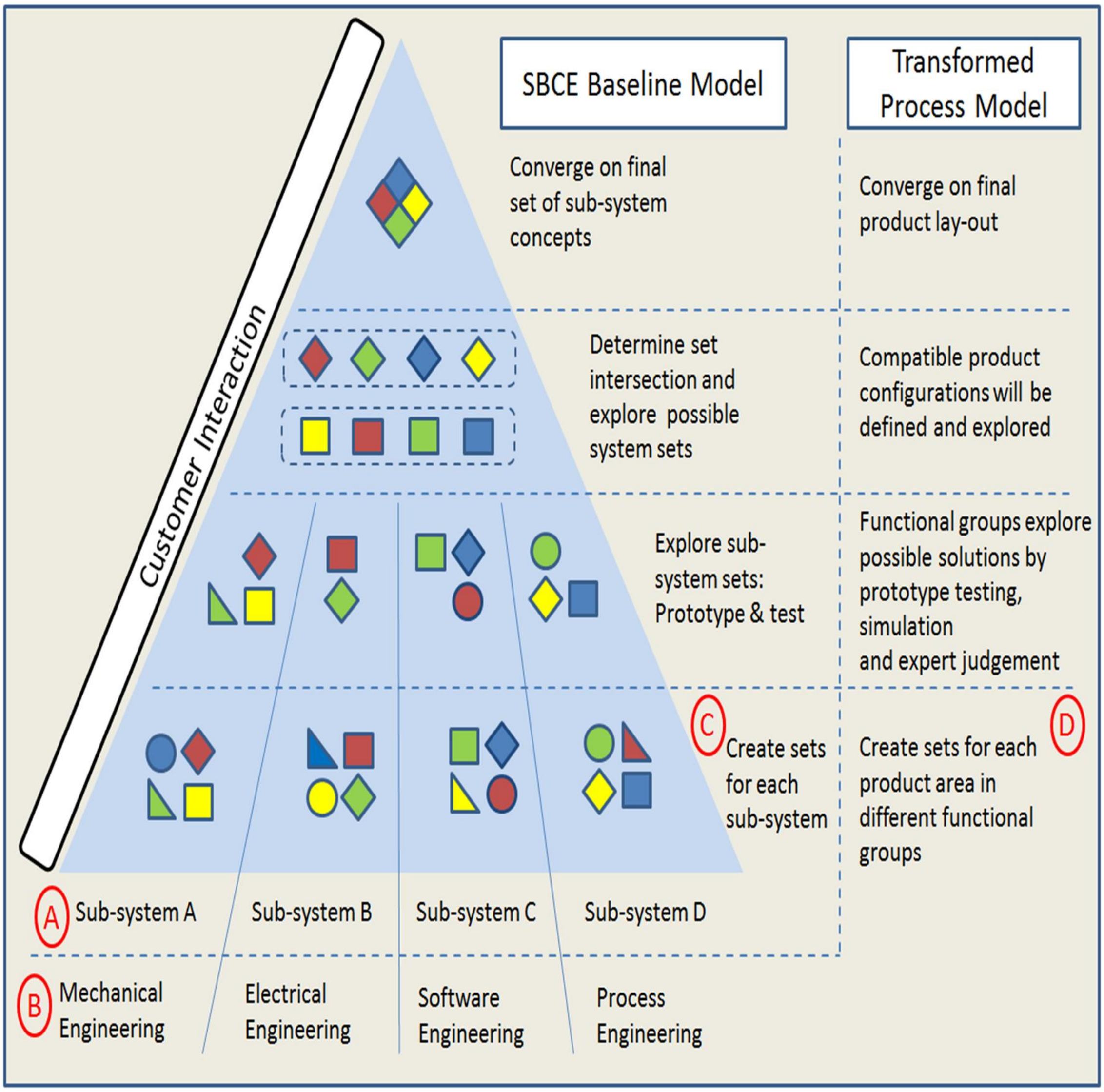

Figure 5-5 Activities clarification

5.6 Step 4: Requirements for the new process model

The intention of the field study presented in Chapter 4 was to analyze the current product development model within the collaborating company in relation to the set-based concurrent engineering good practices. The purpose of this was to identify the potential areas for improvement and the need for formal implementation of certain SBCE tools and techniques to be embedded in the current PD model. Based on the results from that field study the requirements for the new product development process model have been defined.

In accordance with the requirements defined, three transformation categories have been defined as a guideline for the transformation process:

Transformation categories	
A	Keep process step from existing process model
B	Modify existing process step towards a set-based approach
C	New process step to be embedded from the SBCE baseline model

Table 5-3 Transformation categories

Category A: Existing process steps which are considered to be effective as a result from the data analysis of the field study will be kept (Category A).

Example: Process step 3.4 (“Capture knowledge and evaluate”) is already practiced via knowledge data base and frequently updated design guidelines.

Category B: Existing process steps which already tackles certain set-based aspects but require an upgrade towards SBCE.

Example: Process step 1.1 (“Classify project type”) is already considered in the current process model but an innovation classification is missing and needs to be addressed.

Category C: Process steps from the SBCE baseline model which are completely missing in the existing process model will be embedded into the new transformed process model, unless it is not a requirement coming out from the field study.

Example: Process step 1.2 (“Explore customer value”) is neither well established nor formally implemented in the current product development process and will be embedded into the new set-based concurrent engineering process model.

The transformation categories defined have been applied to the whole process. The results have been summarized in Table 4-4 (Requirement Matrix):

Requirement Matrix			
Process steps from SBCE baseline model	Require-ment from data analysis [Y/N]	Current practice	Trans-formation Category [A,B,C]
Phase 1: Value Research			
1.1 Classify project type	Y	Projects are classified in relation to the scope of work (minor modification, critical changes, new product development) but an innovation classification is missing.	B
1.2 Explore customer value	Y	Customer value exploration is neither well established nor formally implemented in the current product development process.	C
1.3 Align with company strategy	N	---	A
1.4 Translate customer value to designers	Y	As the customer value is usually not thoroughly explored. A translation to all the stakeholder is also not done	B
Phase 2: Map the Design Space			

2.1 Identify Sub-system targets	Y	Referring to step 3 of the transformation methodology the term "sub-system" shall be replaced "product area" in order to fit to the company´s engineering structure (matrix organization).	B
2.2 Decide on the level of innovation to sub-systems	Y	Referring to step 3 of the transformation methodology the term "sub-system" shall be replaced "product area" in order to fit to the company´s engineering structure (matrix organization).	C
2.3 Define feasible regions of design space	Y	---	C
Phase 3: Concept Set development			
3.1 Pull design concepts	N	---	A
3.2 Create sets for each sub-system	Y	Current practice shows significant weak points regarding this activity. Engineers do not systematically produce multiple concepts and tend to start with detailed design too early in the process. Projects often run late due to design iterations.	C
3.3 Explore sub-system sets: Prototype & test	Y	Ruling out weak concepts only based on data is not current practice. Final concept is often chosen based on intuition or experience. Testing or prototyping is usually applied only on the final concept.	C
3.4 Capture knowledge and evaluate	N	---	A
3.5 Communicate set to others	Y	Communicating possible solution variants between different functional groups is not formally integrated in	C

		the current PD model.	
Phase 4: Concept Convergence			
4.1 Determine set intersections	Y	As a "multi-concept" approach on "product-area" level is not common practice in the company also a process step "determine set intersection" is not formally integrated to the current PD model.	C
4.2 Explore system sets	Y	Ruling out weak product configuration only based on data is not current practice. Final product is often chosen based on intuition or experience. Testing or prototyping is usually applied only on one concept.	B
4.3 Seek conceptual robustness	y	Robust design (Taguchi method) is not formally integrated in the current process and its underlying concept is completely unknown by almost 50% of the questionnaire candidates. Some engineers are considering certain aspects of robust design but only based on intuition or experience.	C
4.4 Evaluate sets for lean production	N	---	A
4.5 Being process planning for manufacturing	Y	Manufacturing is not involved for concept selection. They are usually ask to give their comments on the final concept or when the detailed design in already finished.	B
4.6 Converge on final set of sub-system concepts	Y	See comment from point 4.2	B

Phase 5 Detailed Design			
5.1 Release final specification	Y	Current practice is that the specification is frozen very early (3.1) in the process. This results in unnecessary constraints during the design of the product.	B
5.2 Manufacturing provides tolerances	N	---	A
5.3 Full system definition	Y	---	A

Table 5-4 Requirement matrix

5.7 Step 5: Define top level process landscape

Based on the general process lay-out defined during transformation step 2, the single process steps both from the existing process model summary (transformation step 2) and from the SBCE baseline model have been assigned to the new transformed process model whilst taking into account the transformation categories defined in transformation step 4 (requirement matrix).

This implies that some of the existing process steps from the current process model have just been overtaken. Others have been combined or extended towards a more set-based approach and still others have been embedded from the SBCE baseline model.

Figure 5-6 illustrates this approach for Phase 1:

- **Orange arrow:** Process steps 1.1 (Project initiation), 1.3 (Align with company strategy) and 1.4 (Collect data) have been overtaken from the current process model

- **Purple arrow:** Process step 1.2 (Classify project type) is a combined process step taken into account a set-based approach

- **Red arrow:** Process step 1.5 (Explore customer value) and 1.6 (Value translation) have been embedded from the SBCE baseline model

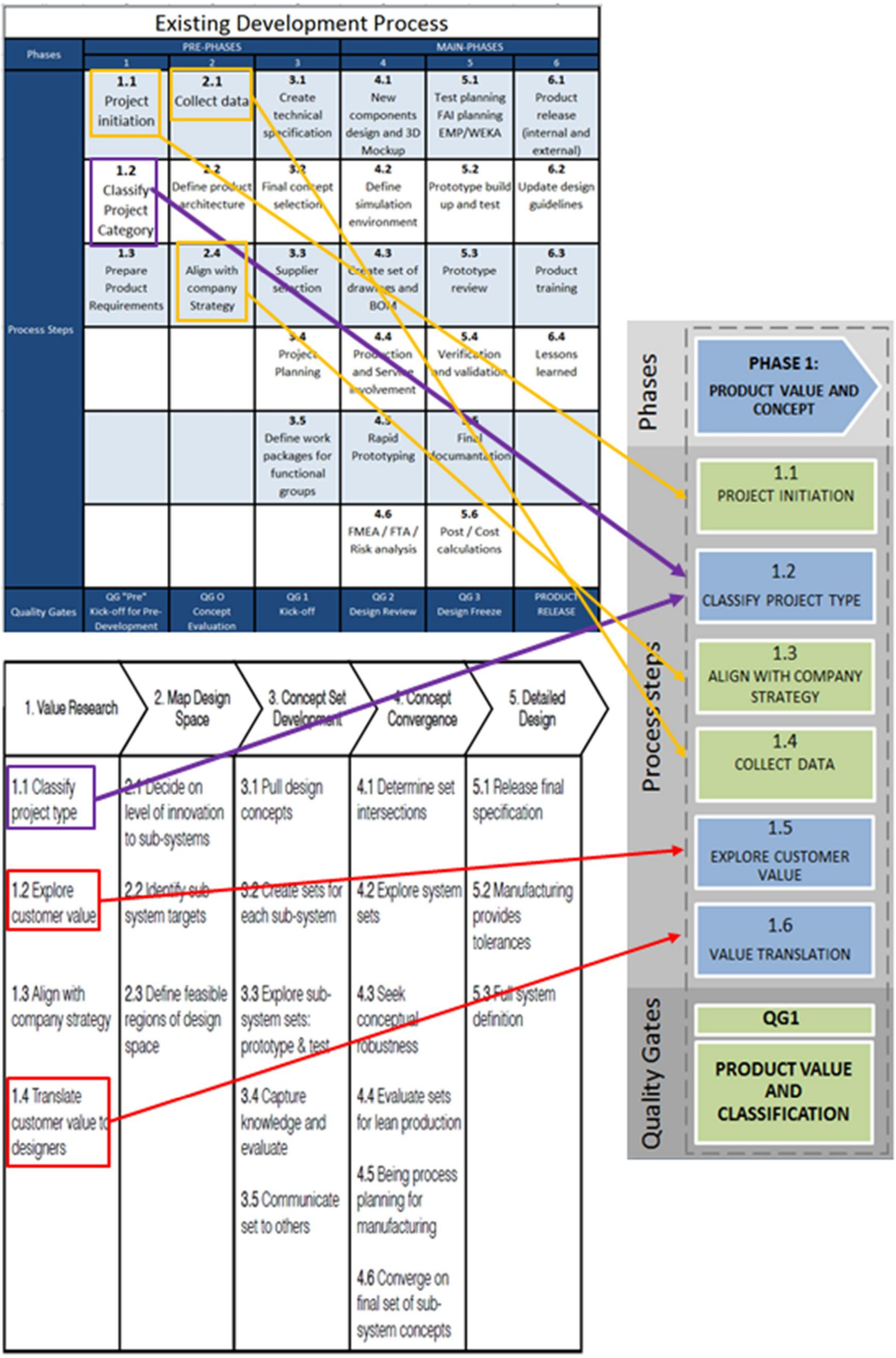

Figure 5-6 Top level process definition

The aforementioned approach has been applied in each phase of the transformed development process model, as shown in Figure 5-3. The process steps either influenced by or embedded from the SBCE baseline model have been marked in blue. The steps that have been overtaken from the existing process model are marked in green (EPM/Existing Process Model):

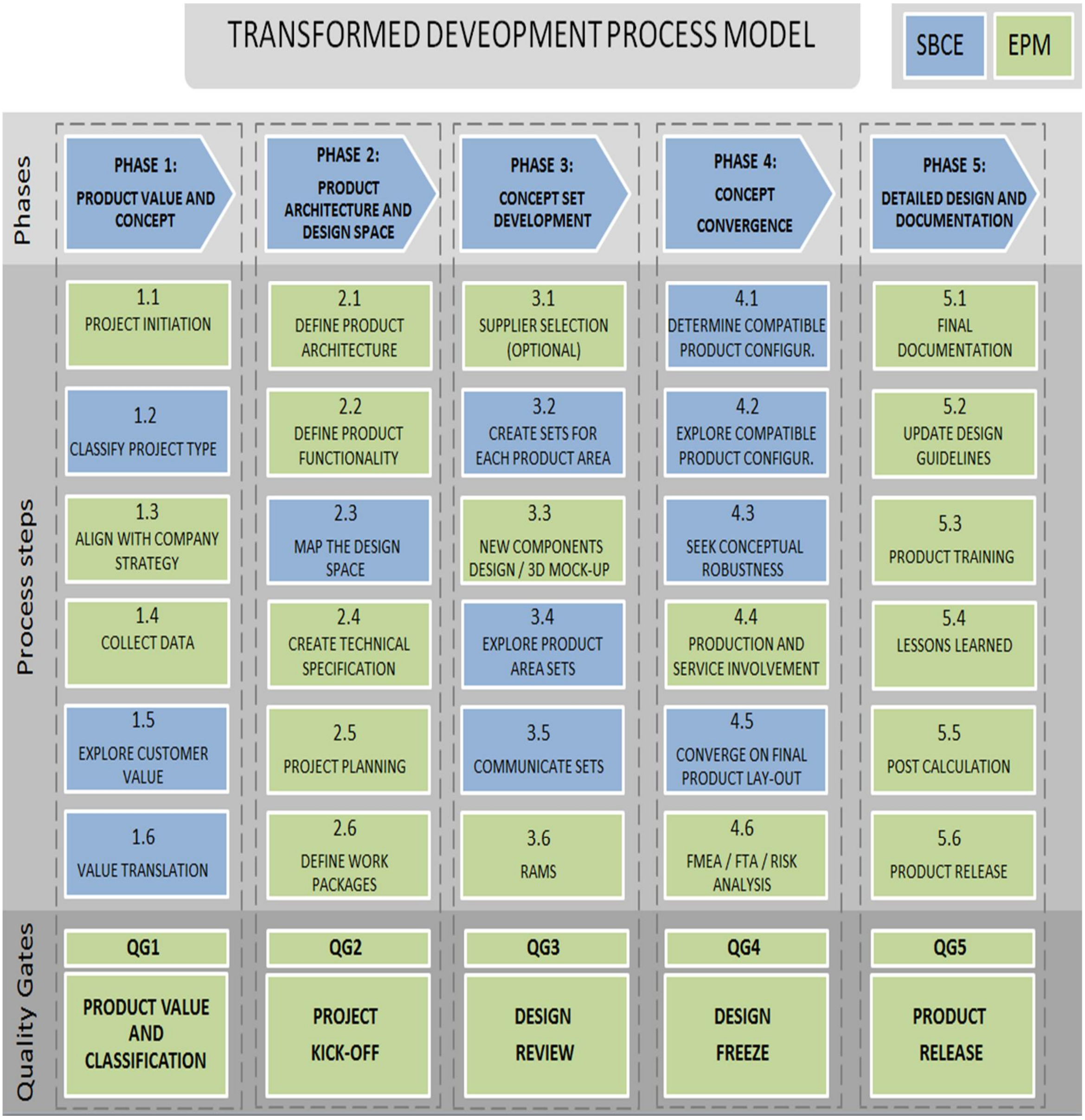

Figure 5-7 Top level process lay-out

5.8 Step 6: Define process layout

During step 6 of the process model transformation the different phases have been specified by defining the activities and tools to be applied in the relative process steps. Each process step has been assigned with a specific activity and a tool to conduct this activity. The activities and tools defined will be further explained during the case study in Chapter 6.

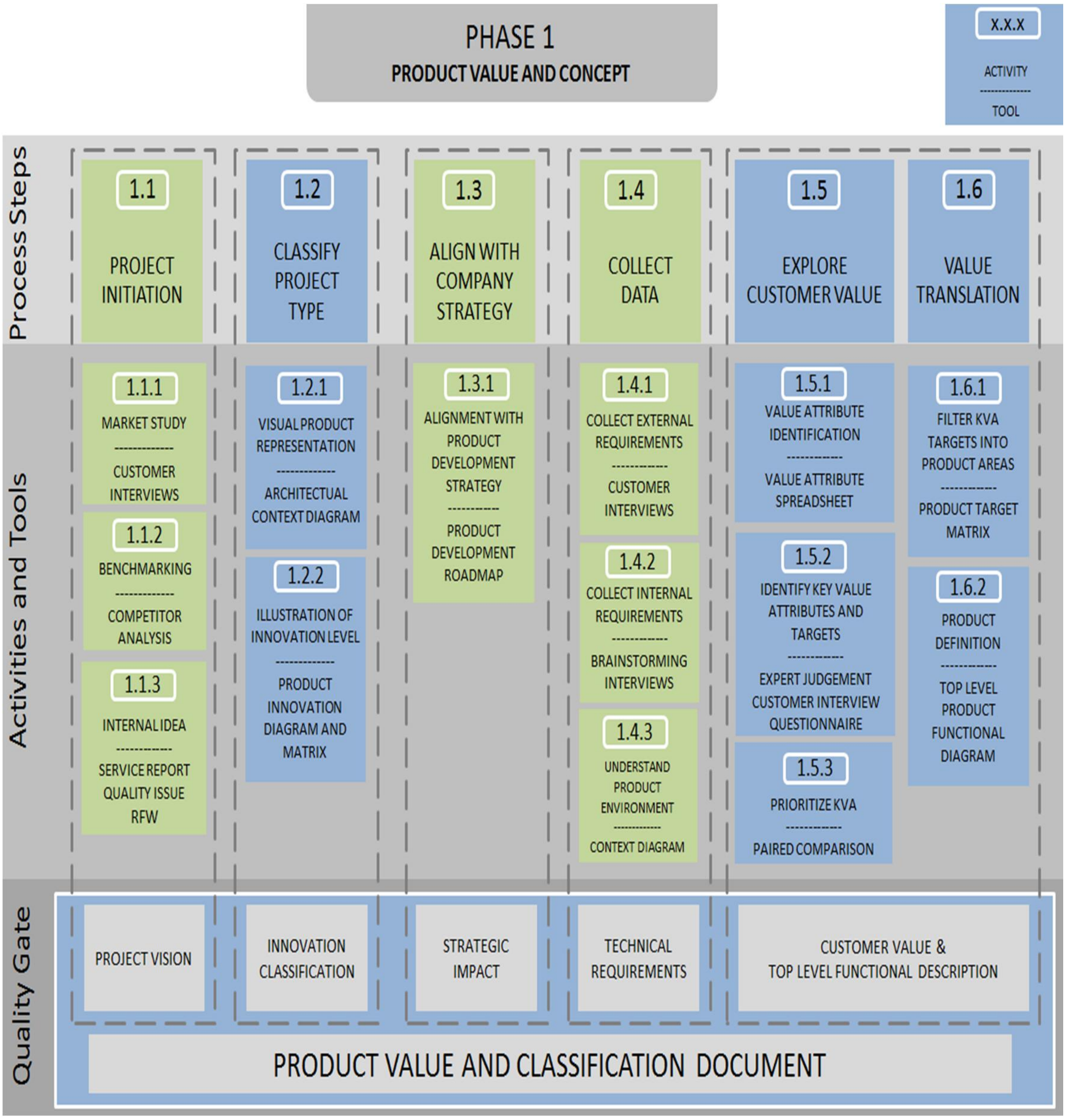

Figure 5-8 Product value and concept

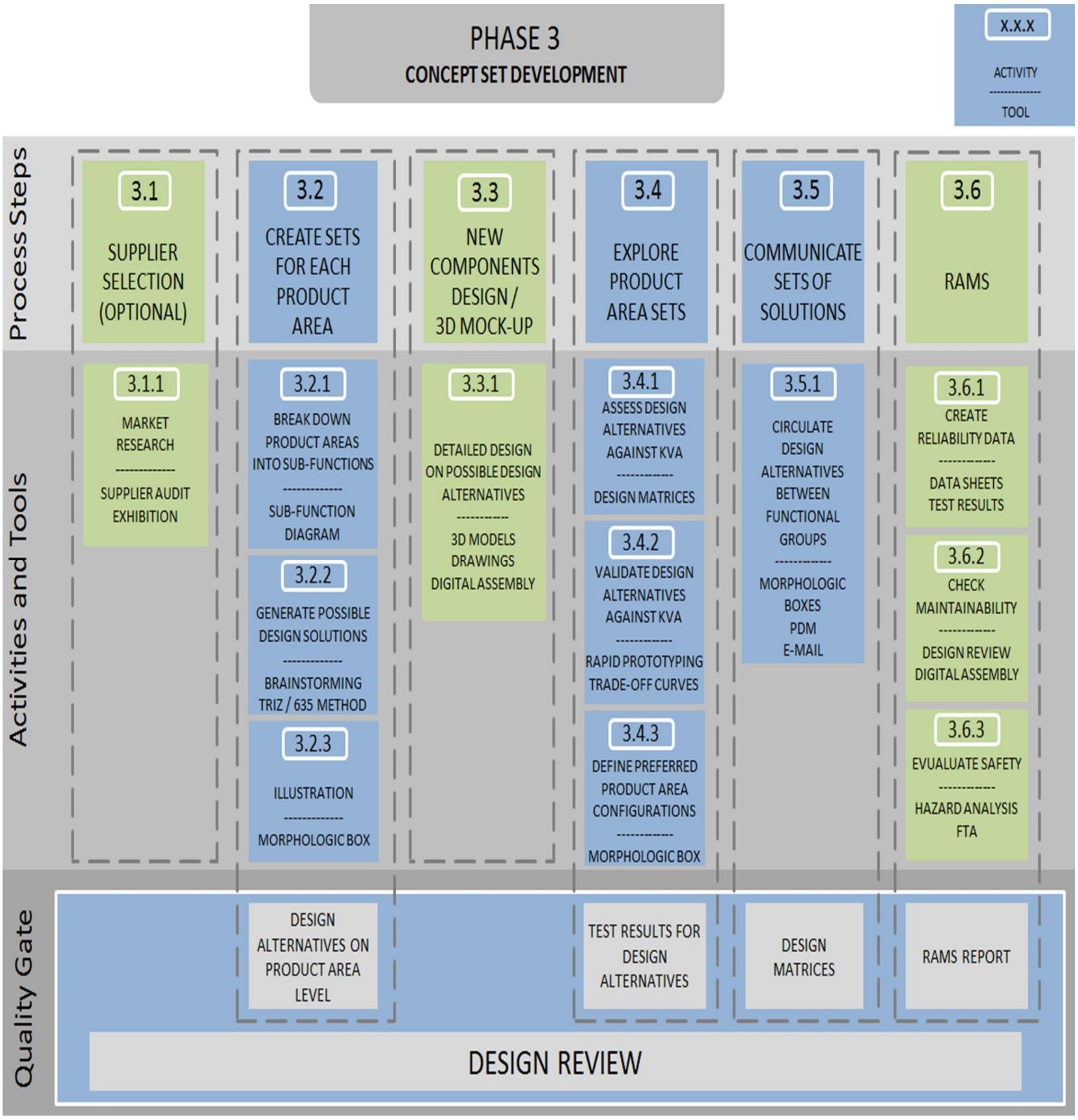

Figure 5-9 Concept set development

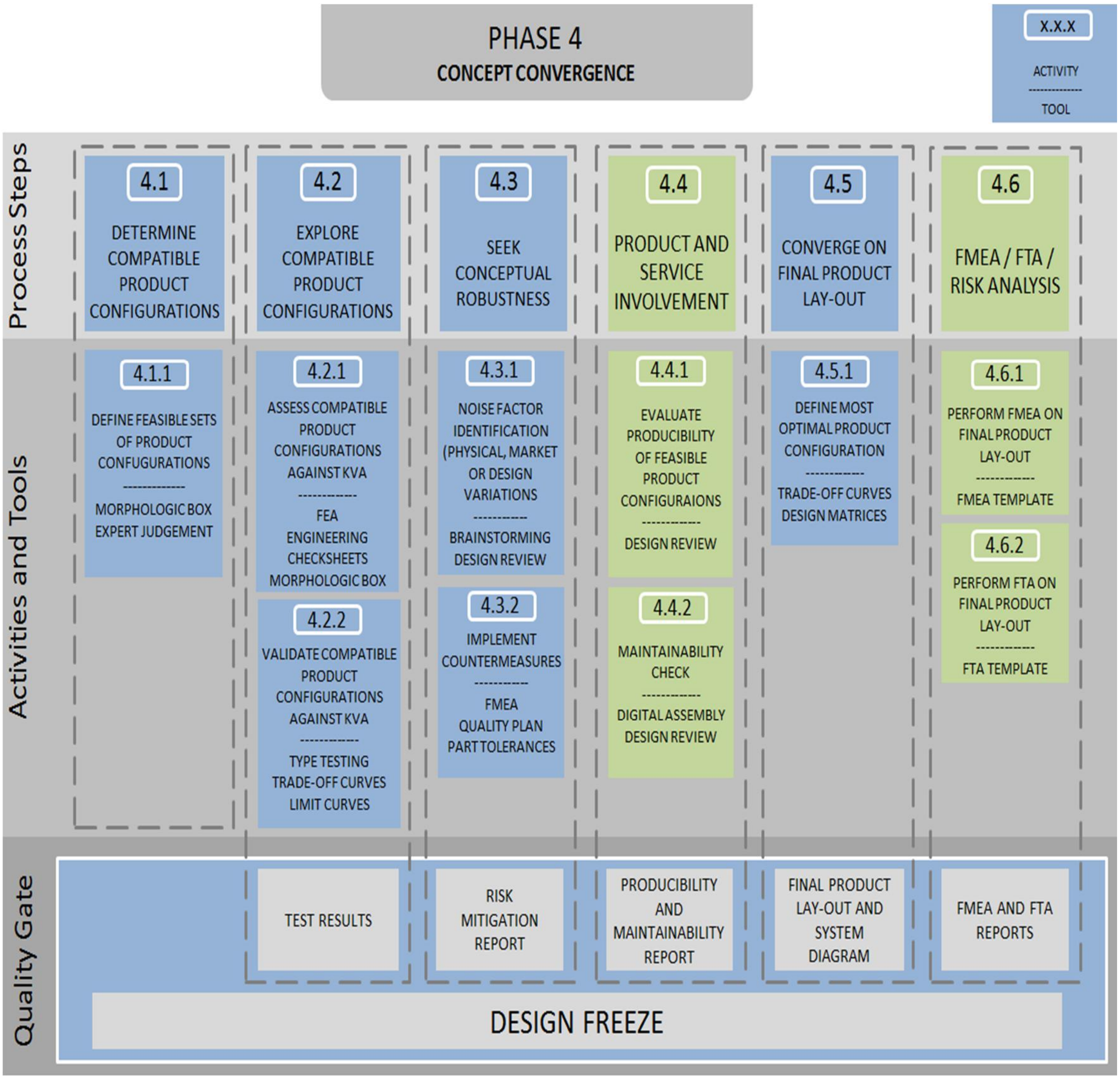

Figure 5-10 Concept convergence

5.9 Summary

This section, related to the process model transformation, presented a research-based approach where principles of set-based concurrent engineering have been embedded into an existing product development model. The potential improvement of the process has been achieved by the development of a structured product development model with well-defined tools and activities (Al-Ashaab et al., 2013). The outcome is a process model with 5 phases, each phase consisting of different process steps. Each process step in turn is conducted suing different activities. In addition, tools have been defined and directly assigned to each activity in order to offer straightforward guidance to the engineers. The main activities focus on core enablers of lean product development, such as value focus, set-based solutions, integrated documentation, knowledge creation and innovation. Each process phase concludes with a quality gate where the current status and common understanding will be aligned between the stakeholders of the project before entering the next phase. The transformed product development process model will be applied and evaluated in a case study, as presented in the following chapter.

6 INDUSTRIAL CASE STUDY

6.1 Introduction

One major challenge for the implementation of SBCE is the limited number and variety of case studies in which the set-based approach has been proved to be successful. “In addition to the original Toyota case study, very little is available about industrial applications of SBCE. This lack of case studies makes design professionals in the industry reluctant to implement SBCE, even if they like the idea, before they see results of real case studies” (Al-Ashaab et al., 2013).

This section aims at implementing the transformed set-based process model in a real case study and providing evidence regarding the practical applicability and efficiency. The purpose of this is to evaluate the value of integrating the good practices of SBCE in enhancing the current PD process. Figure 6.1 shows the developed customised PD based on SBCE as well highlighting the activities that are going to be validated.

The result of the previous chapter was the embedding of certain process steps from the SBCE baseline model into an existing product development process of a company, based on the results of the field study. A formal approach has been defined showing how engineering companies could modify their development processes in a direction in which set based principles will guide the involved stakeholders throughout the projects.

The transformation towards a set-based development process can be summarized and divided into the following procedure:

a) Analysing the As-Is development model with following intention:

- Which aspects of SBCE are already formally integrated within the existing product development process?

- Which aspects of SBCE are missing in the existing development process and where are the main areas for improvement?

b) The flexibility for process modifications must be analyzed. It must be investigated which modifications of the existing process are viable and to what extent, in order to guarantee acceptance of the new model by the stakeholders.

c) Transformation of the development process based on the perceptions obtained in the previous steps. The transformation methodology defined during this research can be applied. The result is a new, modified product development process with embedded set-based process steps including all the necessary activities and tools to be applied within this new approach.

d) The new product development model will be evaluated through a case study by applying it in a pilot project.

6.2 Aim of the case study

The aim of this case study is to use a pilot real industrial project in order to evaluate the newly defined PD model based on the SBCE process model as shown in Figure 5-7. The main intention is clearly not to focus on detailed design and concepts but to show and explain a general procedure, including the proposed activities and tools. Naturally, this evaluation is much more difficult than for instance in the production or manufacturing area, where a real product can be traced during the process and the efficiency can be measured. Therefore, this case study will focus on revealing the newly defined process steps on a real product in order to show opportunities to improve new products in relation to innovational strength, time and cost and minimized design rework. The potential benefit of each process step will be described in contrast to the current practice in the collaborating company.

6.3 Steps to be evaluated

Figure 6-1 indicates the process steps within the scope of evaluation. The process steps to be evaluated are framed in red. They are the newly integrated process steps embedded from the SBCE process model into the transformed development process model of the collaborating company. They have been chosen for validation in order to understand the impact on the current practice in terms of innovation level, creativity and knowledge created.

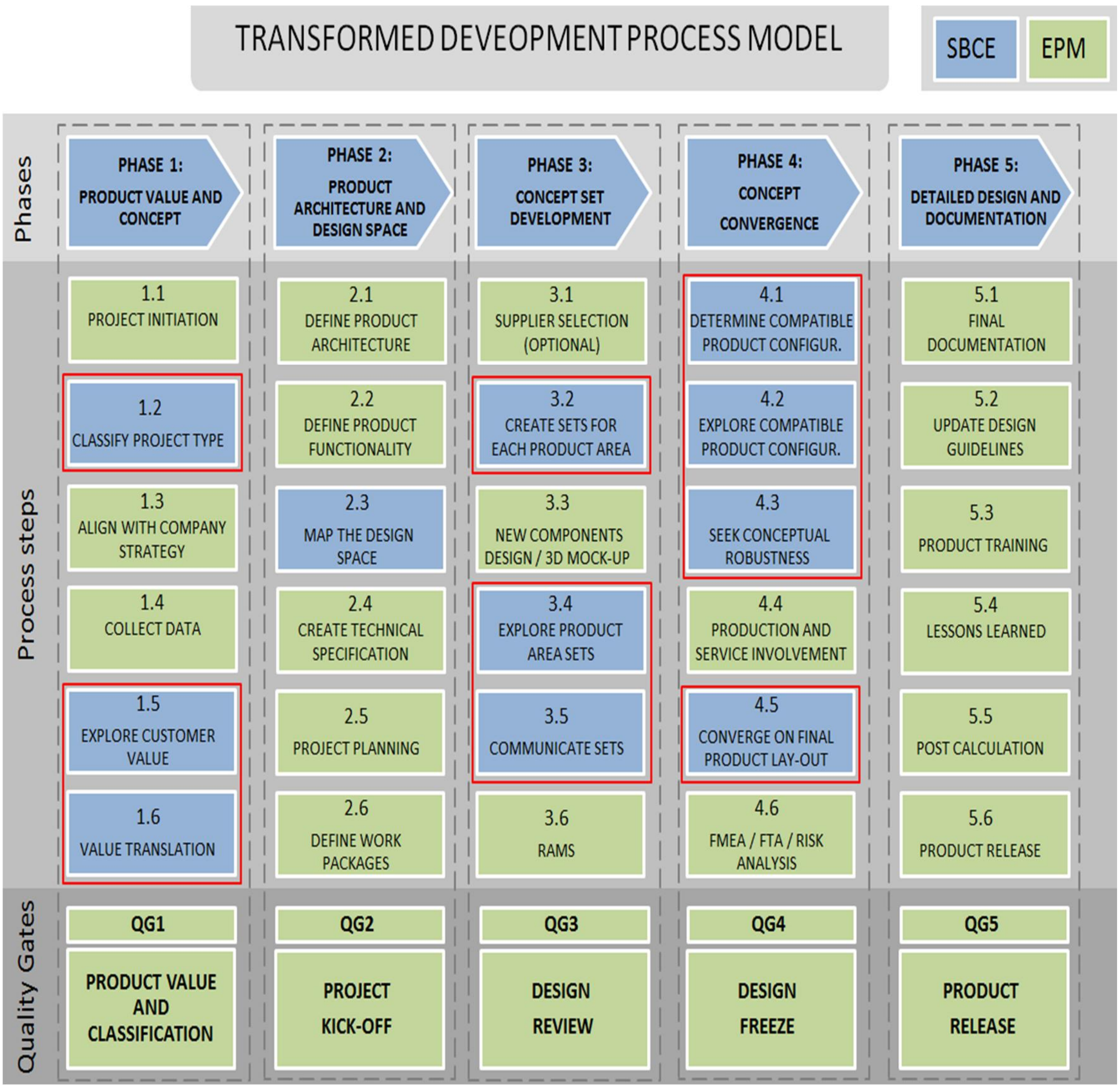

Figure 6-1 Transformed development process model with highlighted SBCE key process steps in red

6.4 Application of the case study

The application of this case study will be a grey-water recycling system for trains, illustrated in Figure 6-2.The system idea is to save fresh water by using the water twice. That means, the water from the wash basin (i.e. grey water) will be treated and filtered and then used to flush the toilet

The main goals of a “grey water recycling system” are:

- reducing the fresh water consumption of the train
- weight and volume reduction of fresh water reservoirs
- increase availability of a train (intervals between fresh water refills)

This project has been chosen for two main reasons. Firstly, it was important to have a project where different functional groups are involved, such as for instance mechanical, electrical or process engineering. This allows for an approach where the product can be subdivided into different product areas (sub-systems) as a starting point for the project. This means that a general "bottom-up"-methodology, where the set development starts in the product area (sub-system) level, can be applied. Secondly, it was relevant to choose a kind of product where the customer value focus, which is one of the core elements of SBCE, can be carefully considered and illustrated.

6.5 Structure of the case study

As illustrated in Figure 6-1 the process phases 1, 3 and 4 of the transformed development process model will be evaluated within this industrial case study.
This is to be performed by the multi-disciplinary team. Each process phase consists of different process steps, for instance process step 1.2 (Classify Project Type) in phase 1 (see Figure 5-7). In order to perform this process step the author has defined different activities and their relative tools to be used (see Figure 5-8, activities 1.2.1 and 1.2.2).

The author has adopted the following approach in order to perform the industrial case study to validate the newly developed SBCE PD model shown in Figures 5-7 to 5-10. Each process step will be illustrated as follows:

1) The aim of each process step will be explained in detail in order to understand and consider the goals to be achieved.
2) The current practice in the collaborating company will be explained based on the findings of the field study (Chapter 4).
3) For each activity of the transformed process model a tool will be proposed and applied.
4) The potential benefit and challenges after the implementation of SBCE influenced process steps and activities will be outlined.

6.6 Phases of the case study

6.6.1 Phase 1: Product value and concept

Step 1.2 Classify Project Type: The aim of this process step is to classify and define the level of innovation to be incorporated to the new product (Khan et al., 2011). Identifying levels of innovation for a new product is important for two main reasons. Firstly, product areas with higher levels of innovation are the ones that should generate more sets of alternative solutions in the coming stages. Secondly, high-innovation product areas are also the ones that are likely to require more development resources (Al-Ashaab et al., 2013).

Current practice in the collaborating company: Projects are classified in relation to the scope of work (minor modification, critical changes, and new product development) but an innovation classification is missing for the different areas of the product.

Proposed tools to enable the activities of process step 1.2:

Activity 1.2.1: In order to create a visual representation of the product within its operational context an architectural diagram illustrating the key element of the system should be used. Figure 6-2 illustrates the architectural diagram of the grey-water recycling system. The diagram shows the top level product configuration by defining the product areas.

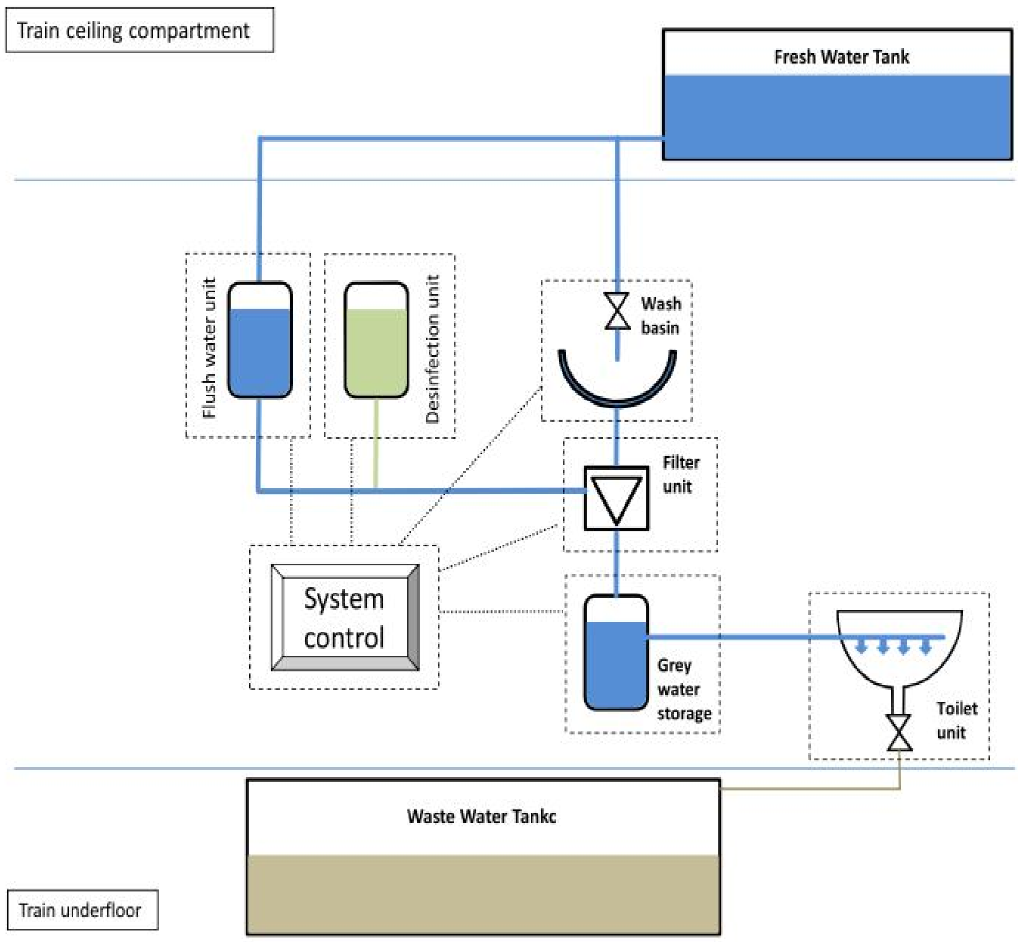

Figure 6-2 Architectural context diagram of the grey-water recycling system

Activity 1.2.2: The innovation level to be applied on the different areas of the product could be illustrated by coloring different elements of the architecture as shown in the key of Figure 6-3. The innovation categories are represented by different colors, as for instance red frame for medium innovation and green for low innovation:

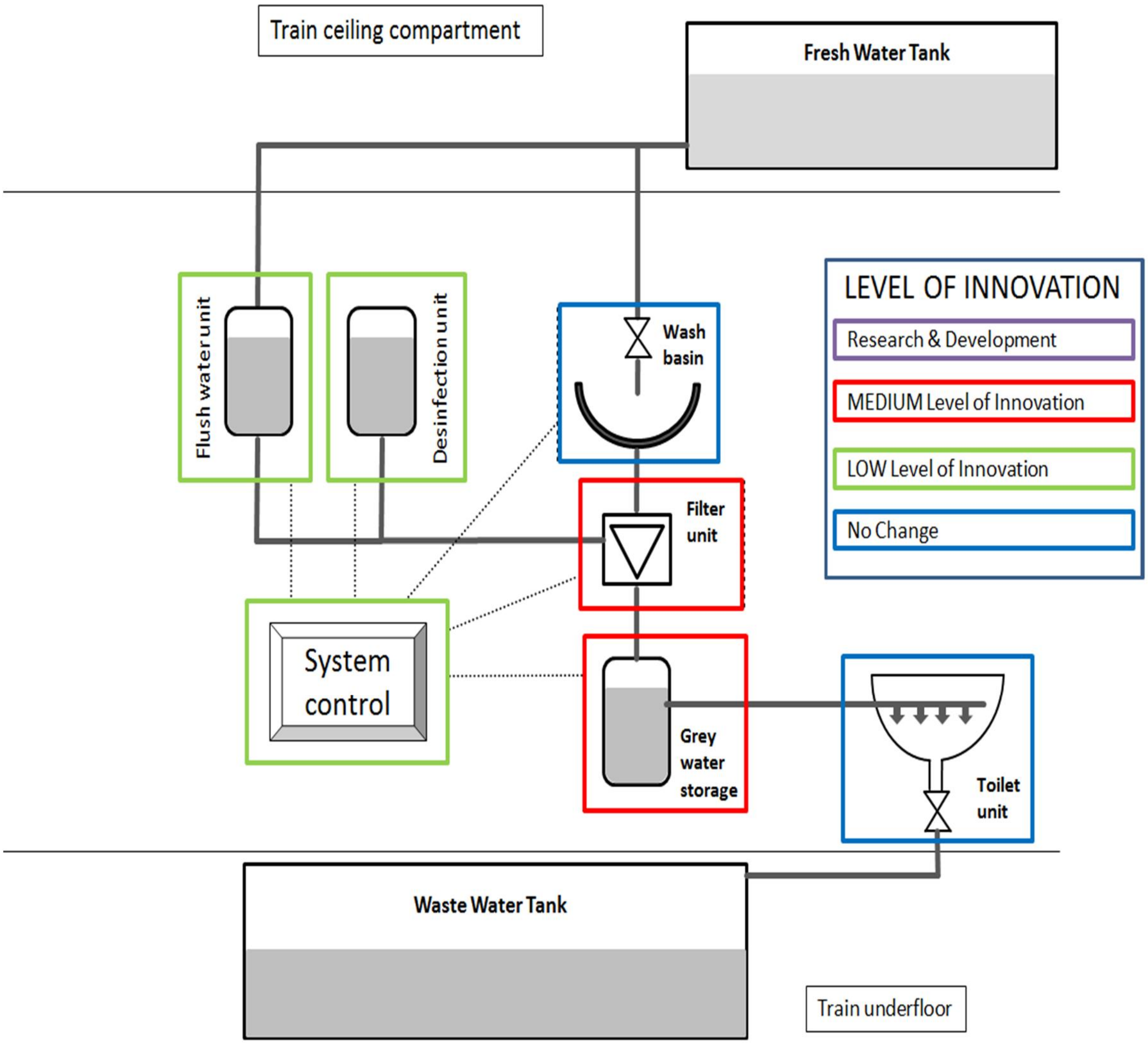

Figure 6-3 Product innovation diagram

The innovation level classifications within this industrial case study have been summarized in Table 6-1, the product innovation matrix:

ID	Product Area	Functional Group	Level of Innovation
1	Filter unit	Mechanical Engineering	Medium
2	Grey water strorage	Mechanical Engineering	Medium
3	System control	Electrical Engineering	Low
4	Flush water unit	Mechanical Engineering	Low
5	Desinfection unit	Process Engineering	Low
6	Toilet unit	Mechanical Engineering	No Change
7	Wash basin	Mechanical Engineering	No Change

Table 6-1 Product innovation matrix

Potential benefit: With the approach proposed for process step 1.2 (Classify Project Type) a clear clarification and illustration of the expected scope of work can be achieved. The stakeholders of the project are aligned relative to the level of innovation to be implemented in their portion of the product. An allocation of resources can be achieved depending on the effort expected for the different product areas. For instance, a product area subjected to high innovation would require significantly more time and effort than a low innovation task.

Step 1.5 Explore Customer Value: Product development by definition plays a key part in defining customer value (Hoppmann et al., 2011) and SBCE is the PD process that focuses on customer value. A key to be successful with a new product development is to consider the customer value as a design input. Customer value should be thoroughly understood in order to determine system targets and will be used throughout product development to evaluate alternative product designs (Khan et al., 2011).

Current practice in the collaborating company: The current practice shows less focus on the concept phase as well as undervalued customer and end user´s demands. Customer value exploration is neither well established nor formally implemented in the current product development. Current product development projects are rather focusing on fulfilling technical specifications, such as structural strength, fire behavior or acoustic requirements.

Proposed tools to enable the activities of process step 1.5:

Activities 1.5.1 and 1.5.2: The value attributes will be identified and filtered into key value attributes. A Value Attribute Spreadsheet (Table 5-3) can be used, in which product attributes with potential impact on customer value or end user´s demands are listed. These values and their targets could be identified by performing face to face interviews with the key stakeholders, then validated with expert judgment within the company. Table 6-2 shows the key value attributes and their targets of the case study under consideration.

ID	Value attributes with potential effect on customer value	Identified Key Value Attributes for the actual project	Targets for Key Value Attributes	KVA
1	Cost	**x**	Cost target ≤ X,-	KVA1
2	Compliance			
3	Serviceability			
4	Mounting			
5	Consumptions	**x**	Water consumption ≤ Xl	KVA2
6	Safety			
7	Reliability	**x**	Meantime between failure ≥ X hours	KVA3
8	Availability	**x**	Increase fresh water refilling interval to X days	KVA4
9	Weight	**x**	Weight reduction by X%	KVA5
10	Usability			

11	Quality			
12	Maintainability	**x**	Minimize exchange time of spare parts	KVA6
13	Styling / attractiveness			
14	Ecological requirements			
15	Efficiency			
16	LCC (Life cycle cost)	**x**	≤ X,-/30 years	KVA7
17	Acoustic / sound			
18	Size	**x**	Decrease size of FWT by X%	KVA8
19	Ergonomics			
20	Quality			
21	Transportation			
22	Recycling			
23	EU directives	**x**	Compliance	KVA9
24	Standardisation			
25	Structural Strength			
26	Crashworthiness			
27	EMC / shielding			
28	Environmental conditions			
29	Surface / finishing			
30	Fire behaviour			
31	Interfaces			
32	Human interfaces			
33	Communication			
34	Protection class (IP)			

Table 6-2 Value attributes spreadsheet

Activity 1.5.3: The identified key value attributes shall be prioritized. This can be achieved through a paired comparison, which means that each key value attributes will be scored against all other key value attributes, for example with the following criteria:

- If KVA1 is more important than KVA2 -> 2 points
- If KVA1 is equivalent with KVA2 -> 1 point
- If KVA1 is less important than KVA2 -> 0 points

Criteria	KVA1	KVA2	KVA3	KVA4	KVA5	KVA6	KVA7	KVA8	KVA9	SUM	Ranking
KVA1		1	2	2	2	1	2	2	2	14	1
KVA2	1		2	2	1	1	2	2	2	13	2
KVA3	1	1		2	1	1	1	1	1	9	5
KVA4	1	1	1		2	1	1	1	1	9	5
KVA5	1	0	2	2		1	2	2	2	12	3
KVA6	1	1	2	2	1		1	1	2	11	4
KVA7	2	1	0	1	1	2		1	1	9	5
KVA8	1	1	1	1	1	1	2		0	8	6
KVA9	0	0	1	1	1	1	1	1		6	7

Table 6-3 Paired comparison

The right column in table 6-3 shows a ranking of the key value attributes in relation to their importance between each other. KVA 1, 2, 5 and 6 have been identified as most important for this case study.

Potential benefit: The effort expended in process step 1.5 enables the internal technical personnel of the product development process to focus on the customer value. The functional teams involved will be aligned in relation to the targets to be achieved within their specific area of the product.

Step 1.6 Value Translation: Both the strategic objectives and the understanding of customer value will be translated to the designers involved in the project (Khan et al., 2011). The main intention is to filter the relevant key value attributes into the product areas. A clear visual illustration will be achieved showing which KVA apply for which functional team and what are the relative targets that need to be achieved.

Current practice in the collaborating company: Customer value exploration is neither well established nor formally implemented in the current product development process**.** Therefore, a translation of the identified potential customer value is currently not transported into the different functional groups working on the product.

Proposed tools to enable the activities of process step 1.6:

Activity 1.6.1: The filtering of the KVA into Product areas task shall be done via Product Target Matrix, wherein the KVA can be easily mapped against the different product areas. Table 6-4 shows an example within this industrial case study, where for instance the KVA 5 applies to product areas 1 and 6:

Product Target Matrix		Product areas						
		Mechanical Engineering			Electrical Engineering		Process Engineering	
		Product area 1	Product area 2	Product area 3	Product area 4	Product area 5	Product area 6	Product area 7
Key Value Attributes	KVA1: Cost	x		x		x		
	KVA2: Weight	x		x		x	x	
	KVA3: Consumption			x				x
	KVA4: Maintainability		x	x		x	x	
	KVA5: Reliability	x					x	
	KVA6: Availability	x		x		x		x
	KVA7: Life cycle cost							x
	KVA8: Size		x	x	x		x	
	KVA9: EU directives	x				x	x	x

Table 6-4 Product Target Matrix

Activity 1.6.2: The product set-up including innovation level and target definition for the applicable key value attributes will be defined. A top level system functional diagram (Figure 6-4) can be used, wherein each product area will be assigned with an overview table including a definition of the responsible team, the applicable KVA with targets as well as the innovation level to be implemented.

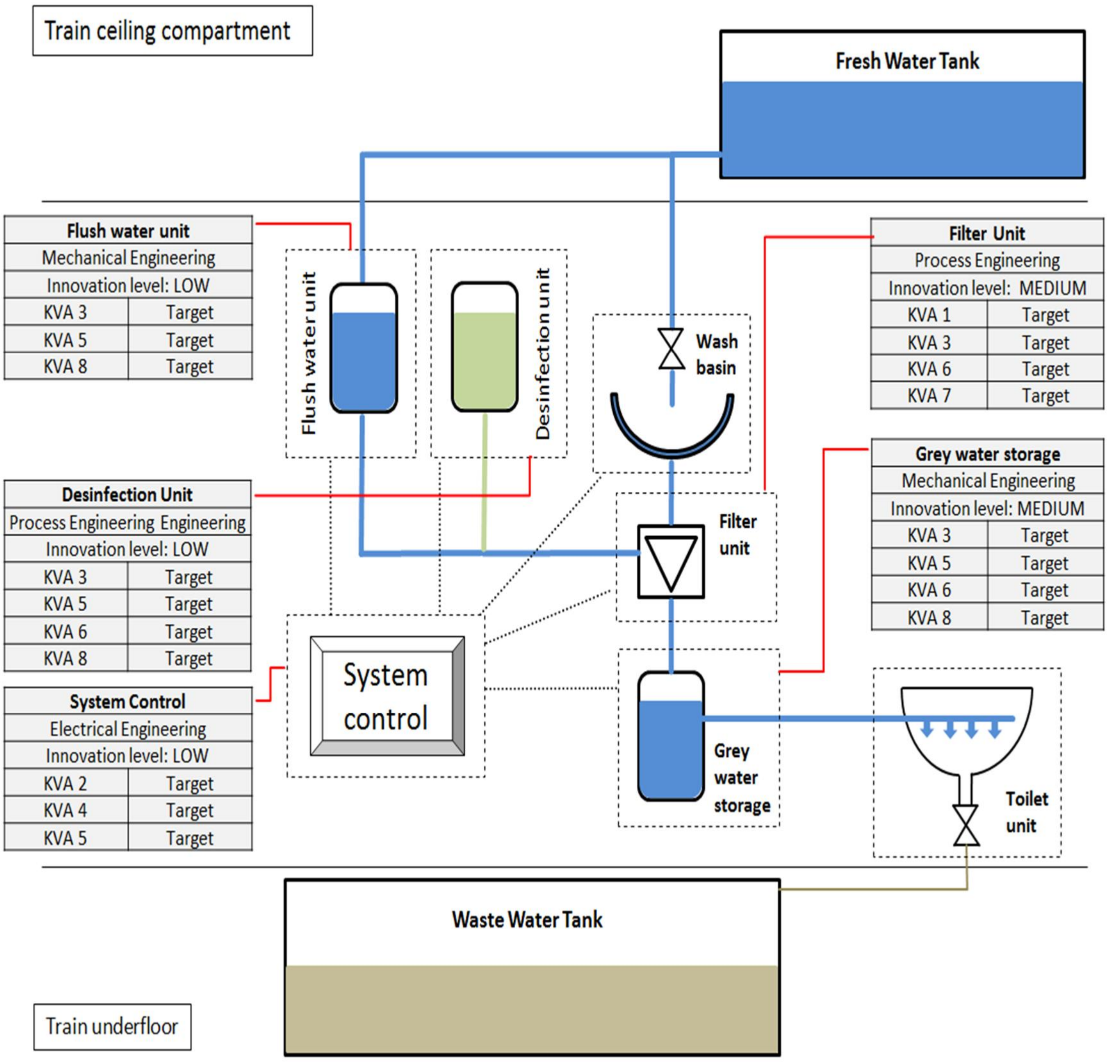

Figure 6-4 Top level product functional diagram

Potential benefit: The activities applied in process step 1.6 ensure an alignment of the project team with the targets to be achieved in relation to the customer value. The top level product functional diagram results in the highest transparency with respect to the influence the different functional groups have when working on their respective areas of the product. In addition, the communication between the various stakeholders of the project will be simplified, as a clear illustrated summary will be made available.

6.6.2 Phase 3: Concept set development

Step 3.2 Create sets for each product area: Within process step 3.2 sets of solutions will be developed for the different areas of the product. Firstly, each product area will be subdivided into their relative sub-functions (Balle and Balle, 2005). Subsequently, the design alternatives for each sub-function will be developed and illustrated in a morphologic box. This provides the opportunity of a bold and simple way of communication of the elaborated design alternatives.

Current practice in the collaborating company: The current practice shows significant weak points regarding this activity. Engineers do not systematically produce multiple concepts and tend to start with detailed design too early in the process. Projects often run late due to design iterations in later stages of a project because the final concept is often chosen based on intuition or experience. Also, testing or prototyping is usually applied only on the final concept.

Proposed tools to enable the activities of process step 3.2:

Activity 3.2.1: A break of each product area into the relative sub-function will be conducted. As an example a sub-function diagram (Figure 6-5) can be used:

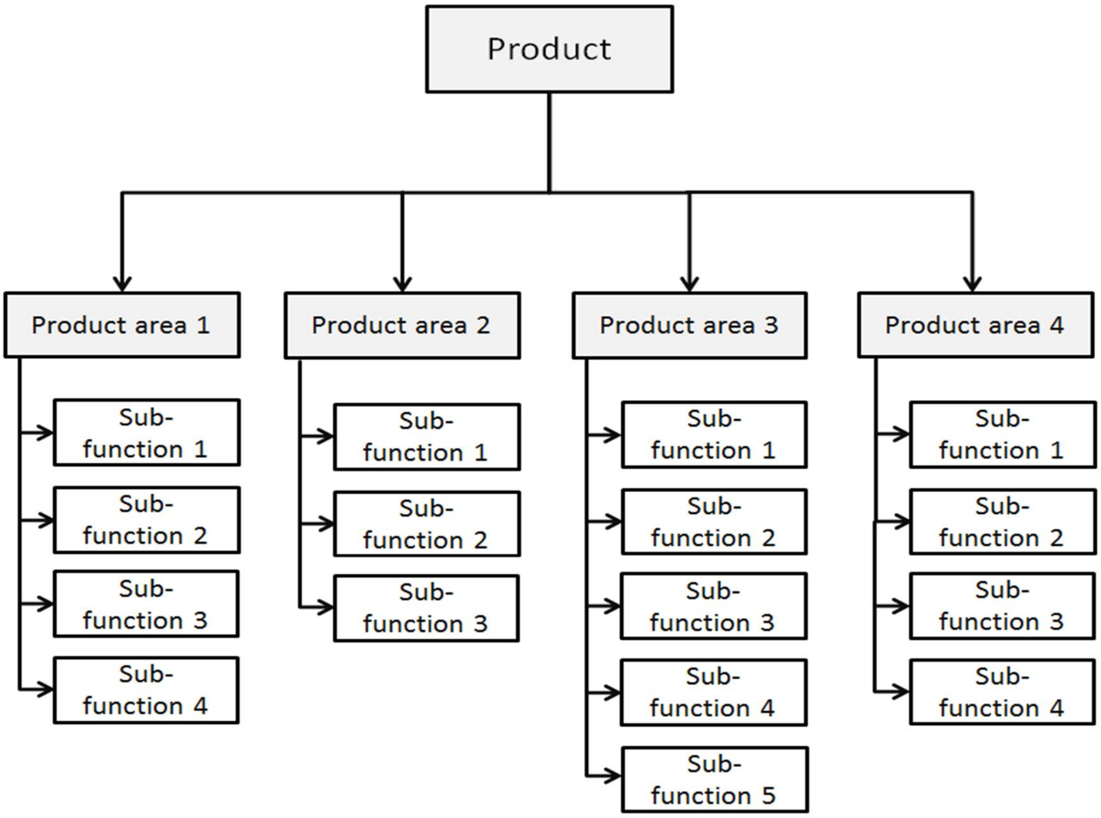

Figure 6-5 Sub-function diagram

As an example the following diagram (Figure 6-6) shows the identified sub-functions of the product area “grey water storage”:

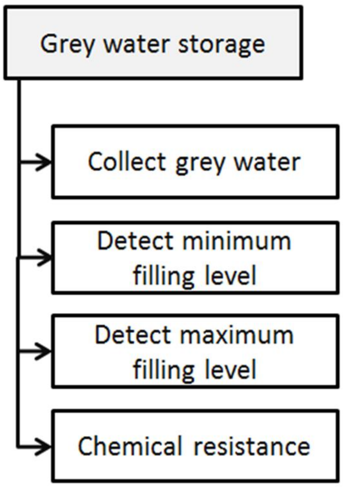

Figure 6-6 List of the sub-functions of the grey water storage element of the system

Activity 3.2.2: Activity 3.2.2: The time for process step 3.2.2 is scheduled for generating design alternatives for each sub-function of the different product areas. This can be achieved by searching solutions from previous projects, pulling new concepts from R&D or creating new design alternatives based on team brainstorming or TRIZ workshops.

Activity 3.2.3: The design alternatives that have been produced within process step 3.2.2 will be illustrated in a morphologic box (Table 6-5). This will support and guide the communication for the next step of the process. The following example shows that for instance four different solutions (A, B, C and D) have been defined for the detection of the minimum filling level:

Sub-functions \ Alternative solutions		1	2	3	4	. . .
1	Collect grey water	A	B	C		. . .
2	Detect minimum filling level	A	B	C	D	. . .
3	Detect maximum filling level	A	B	C	D	. . .
4	Chemical resistance (material)	A	B	C		. . .

Table 6-5 Morphologic box

Potential benefit: The consideration of a broad range of design solutions on sub-function level will most likely increase the probability of finding a more optimal solution than with a conventional point-based approach. SBCE assumes that reasoning and communicating about sets of ideas leads to more robust, optimized systems and greater efficiency than working with one idea at a time, even though the individual steps may look ineffective (Sobek et al., 1999). In addition, a lot of knowledge can be gained from the all the alternatives explored (Ward et al., 1995).

Step 3.4 Explore product area set: Alternative sub-function solutions will be simulated and prototyped, and tested for lifecycle cost, quality, and performance information (Khan, 2011). Weaker solutions will be exposed as well and the confidence in promising design solutions will be increased.

Current practice in the collaborating company: Exploring multiple design alternatives and ruling out weak concepts only based on data is not current practice or formally integrated in the current product development process model. The final concept is often chosen based on intuition or experience. Testing or prototyping is usually applied only on the final product concept. This very often leads to design iterations, especially in later stages of projects.

Proposed tools to enable the activities of process step 3.4:

Activity 3.4.1: The sets of solutions for each sub-function of the product areas will be evaluated against the Key Value Attributes with the support of design matrices (Tables 6-6 and 6-7):

Sub-function 1	Design Alternatives	KVA 1	KVA 2	KVA 5	KVA 6
	1	++	-	+++	-
	2	-	+++	+	++
	3	+++	+	-	-
	4	+	+	++	+++
Excellent: +++ Acceptable: ++ Marginal: + Inacceptable: -					

Table 6-6 Design matrix - sub-function 1 adapted from Sobek (1999)

Sub-function 2	Design Alternatives	KVA 1	KVA 2	KVA 5	KVA 6
	1	-	++	+++	+
	2	++	-	+++	-
	3	+++	+	++	+
Excellent: +++ Acceptable: ++ Marginal: + Inacceptable: -					

Table 6-7 Design matrix - sub-function 2 adapted from Sobek (1999)

Only design solutions which will provide at least an acceptable contribution to each of the key value attributes will be taken forward to the next process step.

Activity 3.4.2: The most promising design alternatives will be validated using tools such as type testing, rapid prototyping or by creating trade-off or limit curves in order to understand their usability for the desired application.

Activity 3.4.3: Based on the results from activity 3.4.2 a few feasible and preferred product area configurations can be defined. This can be illustrated by extending the morphologic box from activity 3.4.1. The case study example is illustrated in Table 6-8:

	Sub-functions \ Alternative solutions	1	2	3	4	. . .
1	Collect grey water	A	B	C		. . .
2	Detect minimum filling level	A	B	C	D	. . .
3	Detect maximum filling level	A	B	C	D	. . .
4	Chemical resistance (material)	A	B	C		. . .

Table 6-8 Preferred product area configurations to design set solutions

Potential benefit: The approach defined for process step 3.4 can reduce the risk of failure because of the considerable number of generated solutions (Al-Ashaab et al., 2013). It ensured that early and critical decisions are made only based on data instead of subjective guessing (Ward et al., 1995). Focusing on convergence, rather than on tweaking a good idea to optimize it, can dramatically reduce the amount of back-tracking in the process (Sobek et al., 1999). Innovation and creativity are enabled and a lot of knowledge can be gained from set-based solutions (Ward et al., 1995).

Step 3.5 Communicate sets of solutions: Each functional group will present their set of feasible product area solutions to the other teams at an event in order to get feedback and understand constraints (Khan et al., 2011). Design teams will evaluate sets based on their constraints and will provide guidance to each other; any design decision after this point should be valid for the different sets and not affected by other sets (Khan et al., 2011). Communicating whole sets of possibilities simultaneously ensures that communication and decisions remain valid throughout the project's life (Ward et al., 1995).

Current practice in the collaborating company: The systematically ensured communication about design alternatives between the different functional groups is not formally integrated in the current development process model and thus not perceived as good practice in the company.

Proposed tools to enable the activities of process step 3.5:

Activity 3.5.1: The design alternatives of the different functional groups will be illustrated within morphologic boxes and made available to other functional groups in order to get feedback and understand constraints and compatibility. A "design solution platform" can be used to make the solutions visible to all stakeholders of the process (Khan, 2011). This can be realized using a shared folder, for instance in the PDM system.

Potential benefit: Having communicated the possibilities of design set solutions, teams can look for the intersections of the different functions, i.e., where the feasible regions overlap. If engineers can identify an intersection, it finds a solution acceptable to all. SBCE assumes that reasoning and communicating about sets of ideas leads to more robust, optimized systems and greater efficiency than working with one idea at a time, even though the individual steps may look ineffective (Sobek et al., 1999).

6.6.3 Phase 4: Concept convergence

Step 4.1 Determine compatible product configurations: The approach for phase 4 is very similar to that of phase 3, but applied at product level instead of product area level. Potential product configurations will be integrated by the intersection of feasible sets, including compatibility and interdependencies between product area solutions (Khan et al., 2011).

Current practice in the collaborating company: The current practice shows significant shortcomings regarding such an activity. Engineers do not systematically produce multiple concepts on product level as identified in Figure 4-4 from the field study. Projects often run late due to design re-work in later stages of a project because the final product configuration is often chosen based on intuition or experience. Also, testing or prototyping is usually applied only on the final product configuration.

Proposed tools to enable the activities of process step 4.1:

Activity 4.1.1: By checking the compatibility and interdependencies of the product area sets, feasible product configurations can be determined using a matrix as illustrated in Table 6-9:

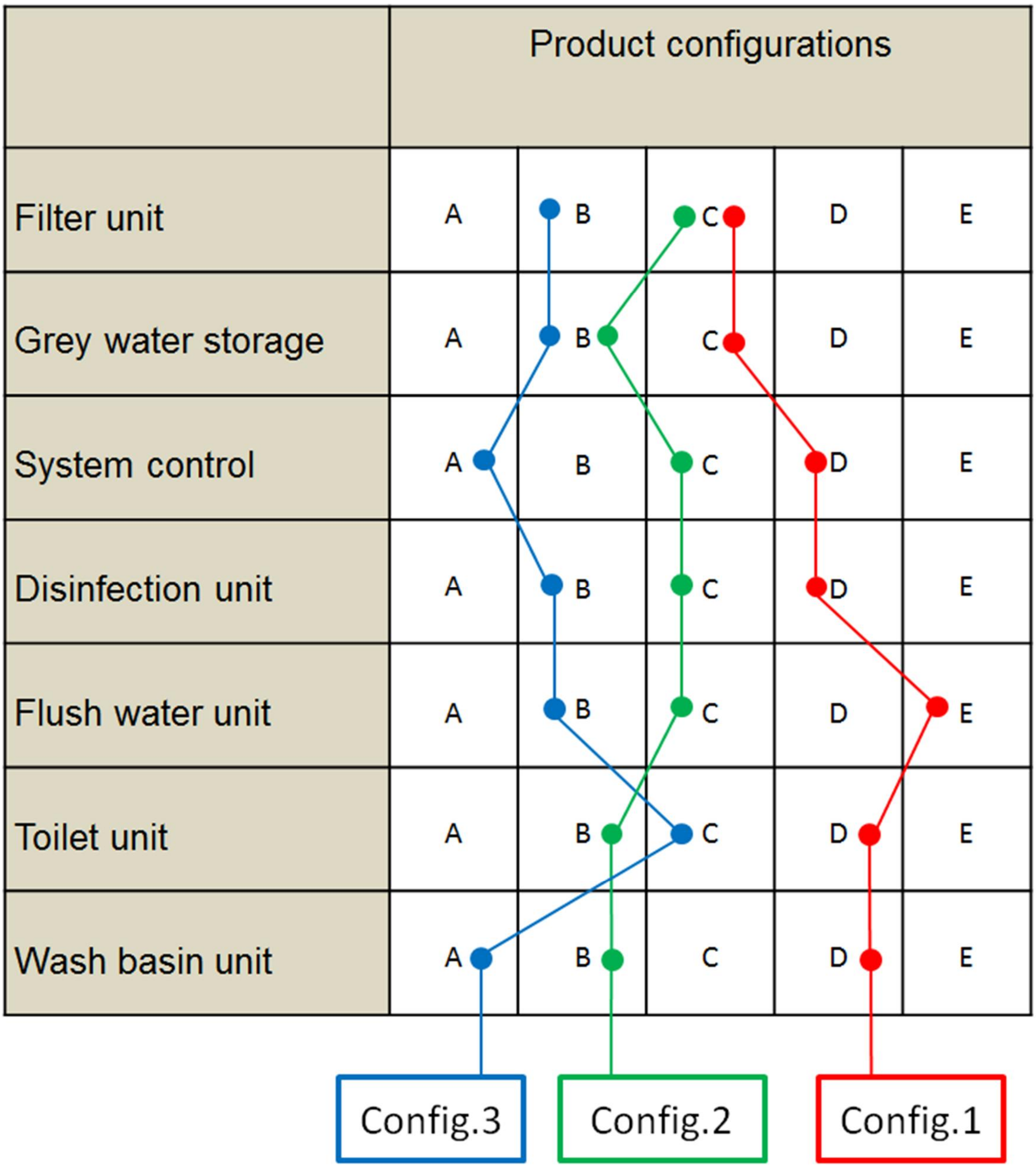

Table 6-9 Sets of product configurations

Potential benefit: The consideration of a broad range of design solutions on product level will most likely increase the probability of finding a more optimal solution than with a conventional point-based approach. In addition a lot of knowledge can be gained from the all the alternatives explored (Ward et al., 1995).

Step 4.2 Explore compatible product configurations: Similar to process step 3.4, where sets on product area level have been explored, different product configurations will be simulated, prototyped and tested against the key value attributes defined earlier in the project. Weak product configurations will be purged as well and the confidence in promising product configurations will be increased.

Current practice in the collaborating company: Exploring multiple product configurations and ruling out weak concepts only based on data is not current practice or formally integrated in the current product development process model. The final product configuration is often chosen based on intuition or experience. Testing or prototyping is usually applied only on the final product configuration. This very often leads to design iterations, especially during later stages of projects.

Proposed tools to enable the activities of process step 4.2:

Activity 4.2.1: The compatible product configurations will be evaluated against the Key Value Attributes with support of a product configuration matrix (Table 6-10):

Product Configurations	KVA 1	KVA 2	KVA 5	KVA 6
1	++	-	+++	-
2	-	+++	+	++
3	+++	+	-	-
4	+	+	++	+++
Excellent: +++ Acceptable: ++ Marginal: + Inacceptable: -				

Table 6-10 Product configuration matrix

Activity 4.2.2: Similar to activity 3.4.2, where sets of alternatives on product area level have been evaluated against the key value attributes, the same activity will be applied of product level. The most promising product configurations will be validated using tools such as type testing, rapid prototyping or by creating trade-off or limit curves in order to understand its usability for the desired application.

Potential benefit: The potential benefits are similar to the ones from process step 3.4, but on the product level. The risk of sub-optimal solutions can be reduced due to the considerable number of generated solutions (Al-Ashaab et al., 2013) while a lot of knowledge can be gained for this as well as for future projects.

Step 4.3 SEEK CONCEPTUAL ROBUSTNESS: Based on Toyota's Product Development System, Sobek et al. (1999) broadly defined the term conceptual robustness based on three forms of variation: physical, design and market (Cabello et al., 2012). Taguchi et al. (2000) defined Conceptual Robustness as "the state where the technology, product, or process performance is minimally sensitive to factors causing variability (either in manufacturing or user's environment) and aging at the lowest manufacturing cost." Standardization and flexible manufacturing are two strategies used to achieve a robust product design in relation to the definition above. "Developing a robust product platform architecture brings an important competitive advantage to a company. The major benefits are reduced design efforts and time-to-market for future generations of the product" (Cabello et al., 2012).

Current practice in the collaborating company: Robust design practices (i.e. Taguchi method) are not formally integrated in the current process and its underlying concept is completely unknown by the stakeholders of the development projects. Some engineers are considering certain aspects of robust design but only based on intuition.

Proposed tools to enable the activities of process step 4.3:

Activity 4.3.1 and 4.3.2: Within the activities 4.3.1 and 4.3.2 possible noise factors applicable to the product will be determined with the help of team brainstorming. Subsequently, the relative countermeasures will be assigned to each noise factors. As an example (line 1) low temperature condition has been defined as a physical noise factor. A possible countermeasure can be to implement a freeze drain mechanism which empties the system of water. The results within this industrial case study are illustrated in Table 6-11:

ID	Noise factors	Countermeasure
	Related to Physical variations	
1	Low temperature conditions	Implement freeze drain mechanism
2	High temperature conditions	Perform climate chamber test
3	Shock and vibration	Perform shock and vibration test
4	.....	
5	...	
6	.	
7		
	Related to Market variations	
8	Different tank volume required from customer side	Implement flexibility in the mould for tank manufacturing
9	Different sensor positioning required (e.g. minimum level detection)	Allow for different positioning in mould by e.g. inserts
10	.....	
11	...	

12	.	
13		
	Related to Design variations	
14	Malfunction on component level (e.g. level sensor	FMEA
15	Filter clogged	Implement filter backwashing
16	.....	
17	...	
18	.	

Table 6-11 Noise factors and countermeasure examples for the grey water recycling system

As a concrete example within this case study Noise Factor ID 8 will be further investigated at this point. The tank volume of the grey water storage (Figure 6-2) has been identified as a potential variation for future projects depending on the actual customer request. Therefore, it has been defined a countermeasure in relation to the tooling lay-out, which will allow for easy adjustment in size without the necessity for a complete new tooling in case the customer prefers a different capacity. This will be achieved by realizing the middle part of the mould as variable and exchangeable part, which then determines the final size of the tank. This simple tooling adapter can, corresponding to the customer request, be easily manufactured within a very short time and at low cost. The upper and lower parts of the tank instead, which include all the peripheric interfaces of the product, may be kept across projects.

Potential benefit: The solution described in the previous paragraph considers both the standardization aspect of the product in relation to the interfaces as well as the flexible manufacturing approach in relation to potential variation in terms of customer request (different capacities). This approach can lead to limited design effort and cost as well as to a reduced time-to-market.

Step 4.5 CONVERGE ON FINAL PRODUCT LAY-OUT: After narrowing the product configuration sets gradually and increasing in detail as the concepts progress, a final set can be converged based on the knowledge gained from analysis; the final set will not be changed except in unavoidable circumstances and will be finalized at a design freeze event where the final design will be presented approved (Khan, 2011).

Current practice in the collaborating company: A multi-concept approach is not current practice and not formally integrated in the development process.

Proposed tools to enable the activities of process step 4.5:

Activity 4.5.1: Based on the evaluations and knowledge captured, sub-optimal product designs will be eliminated and the proven optimal design from the product is finalized. Test results, trade-off curves and degree of fulfillment in relation to the key value attributes need to be thoroughly analyzed and evaluated in order to converge on the final product lay-out.

Potential benefit: Based on the evaluations and knowledge captured, sub-optimal product designs will be eliminated and the proven optimal design from the system can be finalized. This can be achieved by properly analyzing test result of the final set of possible product configurations.

6.7 Summary

The chapter presented the application of the SBCE activities which have been integrated into the current PD model of the collaborating company. The case study demonstrated a possible scenario of the application of SBCE in the pilot industrial project. The different steps and their related activities and the associated tools have been discussed at a level of detail in order to provide an appreciation of the application of the SBCE in developing a new product. The work of each phase of the transformed process SBCE model, as shown in Figure 6-1, is going to be reviewed in a quality gate where the different stakeholders and members of functional groups present the work that has been done in order to create a common understanding and alignment of the current progress and solutions. This is to facilitate agreement about the final decision to pass the project to the next phase.

7 DISCUSSION AND CONCLUSION

7.1 Introduction

This chapter concludes the research results and explains the contribution to the knowledge. The key findings as well as the main potential benefits of the proposed lean transformation presented in this thesis will be discussed.

7.2 Discussion

The work presented aimed at enhancing a conventional product development process by integrating the good practices of set-based concurrent engineering.

As described in the literature, set-based concurrent engineering seemed to be a promising approach to perform product development projects with several potential benefits in relation to conventional approaches. The author agrees with Al-Ashaab et al. (2013) that a number of obstacles need to be overcome, before SBCE could become a standard approach in product development. The main challenge is the lack of a clear structured SBCE model with well-defined process steps, activities and tools, as SBCE is usually just presented as a set of generic descriptive principles (Al-Ashaab et al., 2013). The second challenge is a missing guideline or step-by-step methodology for how to integrate or embed set-based process steps into an existing product development process landscape.

The work presented contributes to the knowledge in relation to the above mentioned research gaps. Firstly, the outcome is a well-defined set-based product development process model with clearly associated process steps, tools and activities. Secondly, it presents a systematic and detailed guideline for how the transformation from a conventional product development process towards a set-based product development model can be performed by embedding SBCE principles to enhance the leanness of the process. Another contribution of the presented work is the implementation and evaluation in a real industrial case study.

The main potential benefits of the transformed process model, as described and illustrated in this research are:

- highlighted the increased level of innovation in the process as a result of working with multiple solutions simultaneously
- decreased the level of risk in terms of rework in later design stages, because potential design alternatives are available
- explicit focus on customer value throughout the process by consideration of key value attributes
- creation of useful knowledge through studying and debating on multiple design configurations
- effective way of working by clearly defined and associated process steps, tools and activities

7.3 Research Limitation

The "multi-concept" product development approach presented in this work needs further validation by the application in real product development projects in order to finally understand its impact in terms of improved product development performance. To achieve this, a holistic initiative within the company would be necessary to manage this consequent change. This is considered to be a major task which would require a lot of resources and commitment, because a standard procedure for implementing a new process model is not available and hence is a potential area of research in future.

A further challenge is that a set-based approach in product development is more complex than a point-based approach and requires higher skill sets and more experience from the engineers (Ward, 1995). At first glance the consideration of multiple alternatives appears as extra work and the stakeholders of the development project are usually difficult to persuade. Naturally, people desire a high degree of certitude which supports an early definition on a concept. A continuous containment of alternative solutions requires more effort and passion (Lenders, 2009).

7.4 Conclusion

- Both the reviewed literature and the field study showed there are several product development (PD) challenges that need to be addressed. The current PD approaches are falling short in addressing such challenges.
- The analysis of the SBCE principles provides good promises to address such PD challenges. However, there is the lack of a clear structured SBCE model with well-defined process steps, activities and tools.
- The research provided a practical approach to fill the gap by providing a step by step transformation methodology to support companies to integrate the SBCE good practices into their traditional PD model.
- The definition of the new PD process model based on SBCE principles show, companies could adopt the approach by the transformation without the need to make a drastic change to the structure of their engineering organisation. The approach described is not company specific and can be adopted by or from any other company
- The case study using the pilot project provided a good evaluation for the value of the SBCE application.

- The transformed product development process model contains several new aspects that enforces innovation and creativity as well as decreasing the risk of rework at later stages of the process
- The full transformation into the whole organisation would require full support of the top management and the different functional groups.

7.5 Future work

The following could be considered as potential future work which need to be addressed:

- Involve more functional groups in the transformation process as well as the application of the pilot projects.
- Address in detail the knowledge-based environment to enable the SBCE applications.
- To further develop the tools and their integration to enable and enhance application of the SBCE.
- Addressing in more detail the resources needed to enable full implementation of the SBCE.
- Investigation of the cost-benefit analysis of SBCE

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APPENDICES

Appendix A Structured questionnaire related to SBCE

Appendix A

Structured questionnaire related to

Set-based Concurrent Engineering

Interviewee details

Name	
Job title	
Role in organisation	
Years of experience in current role	

Contents

1. Objective of the questionnaire

The objective of this questionnaire is to analyse the current product development model within an engineering company in relation to the set-based concurrent engineering (SBCE) good practices. The collected data can be analysed in order to map the current practices against the SBCE good practices and principles with the goal to identify the challenges and opportunities of improvements.

2. Culture

2.1 Do you see a systematic philosophy for hiring and developing engineers in the company?	Yes	Partly	No
Additional comments (optional):			

2.2 Do you recognize a defined and agreed career path between you and your company?	Yes	Partly	No
Additional comments (optional):			

2.3 Do you recognise a culture or mechanism for capturing, retaining and reusing knowledge in your company?	Yes	Partly	No
Additional comments (optional):			

3. Product Development Process

3.1 General questions

3.1.1 Do you consider the current product development model (DNP Process) effective in guiding your work?			
Guidance of DNP Process	Effectiveness		
	Not effective	Somewhat effective	Effective
DNP Process guiding of product development activities			

3.1.2 How would you describe the current product development model (DNP Process) in terms of visual representation of the process, quality gates, activities and supportive tools?	
Options	Select one
The current product development model is not well communicated and accepted	
The current product development model is well communicated and is developed by a central organization. It is followed during the projects	
The current product development model is well communicated and is developed by a central organization. It is followed properly followed during the projects	
The current product development model is developed and maintained by the development teams themselves but it is not properly followed during the projects	
The current product development model is developed and maintained by the development teams themselves and it is properly followed during the projects	
Additional comments (optional):	

3.1.3 How would you describe your current approach in concept selection for a new product?	
Options	Select one
We quickly decide on a solution and then modify the solution until it meets the design objectives	
We identify multiple concept solutions and select the one which most closely matches the design specification	
We identify multiple concept solutions and select the most promising solution based on subjective intuition and experience	
We identify multiple concept solutions and rule out weaker solutions based on the knowledge gained by prototyping, testing and integration	
Additional comments (optional):	

3.1.4 How are typical development projects running in the company?	
Options	Select one
We are usually starting in a hurry and quickly starting with detailed design instead of exploring multiple design options. Projects often run late due to design iterations and unclear requirements	
We are usually starting in a hurry and quickly starting with detailed design instead of exploring multiple design options. Projects rarely run late and we have few iterations	
We are investing a lot of time at the beginning of the project to explore the technical requirements (customer value) and produce multiple concepts. Nevertheless Projects often run late due to design iterations	
We are investing a lot of time at the beginning of the project to explore the technical requirements (customer value) and produce multiple concepts. Projects rarely run late and we have few iterations	
Additional comments (optional):	

3.1.5 To which degree do you usually iterate the design before you meet the customer demands?	
Options	Select one
No design iterations necessary (first time right)	
Few design iterations usually occur however within time schedule and budget	
Few design iterations usually occur which is usually critical in terms of time scheduled time and budget	
A lot of design iterations usually occur which is usually critical in terms of time scheduled time and budget	
Additional comments (optional):	

3.1.6 Which of the following aspects do you think need more attention within the current product development model (DNP process)?	
Options	Select as appropriate
DNP process is not well communicated and accepted	
Understanding of the customer value	
Understanding of the end user desires	
Engineers are forced to spend time on unnecessary documentation	
More focus on the concept phase	
The communication between different functional groups (mechanical, electrical, software, etc.)	
The communication between Design and Manufacturing	
The communication between Design and Quality	
The communication between Design and Supplier	
Too many sign-offs required	
Others:	

3.1.7 Which of the following problems do you observe within the product development projects in the company?	
Options	Select as appropriate
Too many unplanned design iterations	
Products do not meet specifications	
Products do not meet cost targets	
Too many design iterations	
Too less standardization and modular design	
Design work being scrapped	
Engineers are overburdened by the quantity of work	
Other functional groups returning flawed work	
Insufficient communication	
Downstream engineers waiting for upstream activities to be complete	
Unnecessary information being produced	
Knowledge reuse	
Insufficient product development lead times	
Insufficient quality of products	
Others:	

3.2 Project initiation and value

3.2.1 Before creating the technical specification for a new product the customer value should be explored and understood properly and it should be worked out what is unique in comparison with competitive products. How is this usually practiced within your company?	
Options	Select one
The term customer value is mostly unknown and there is no systematic approach to explore and define it before starting a project	
Sales and Marketing is responsible to explore and define the customer values and must submit this information to the development team	
Development projects are usually starting based on technical requirements which are prepared/defined by the Project Manager itself. An alignment with a Sales strategy and/or a proper customer involvement has usually not been achieved in recent projects	
The customer has already a well-established process to define their value to be fulfilled	
Additional comments (optional):	

3.2.2 Does the company have a roadmap for development projects in order to have an illustration of the interdependencies between different development projects which allows proper priority setting?	
Options	Select one
A roadmap for development projects does not exist	
A roadmap for development projects does exist but not frequently updated in order to be a helpful tool	
A roadmap for development projects does exist in order to see interdependencies between projects and for priority setting	
Additional comments (optional):	

3.2.3 How is the product concept communicated/translated to the designers to make sure that all involved people have the same input and understanding before starting their developments?	
Options	Select one
There is no systematic and approved approach considered in the current product development process	
The way, level and quality of communication usually done related to this activity is depending on the communication skills of the respective Project Manager	
The Project Manager is creating and circulating a concept paper where he is presenting the vision of the project, quantitative and qualitative objectives as well as product characteristics in order to create a general understanding of the project	
Additional comments (optional):	

3.3 Concept and design approach

3.3.1 How do you make sure that you are designing within the constraints from other functional groups (i.e. manufacturing, service maintainability etc.)?	
Options	Select one
Usually the design will be finished before involving other functional groups. This leads very often to rework and iterations in the design because the constraints from other functional groups were not considered properly	
The Project Manager is deciding when and how to involve other functional groups in order to understand and consider their constraints	
Design reviews are used to discuss the constraints and needs from other functional groups	
Part-specific checklists (including manufacturing constraints, etc.) are available and help to understand the constraints and needs from other functional groups	
Additional comments (optional):	

3.3.2 Do you usually produce multiple design options during a development project?	
Options	Select one
We usually develop only one design for each product	
We usually develop multiple designs and then select the most promising based on experience and intuition	
Sometimes we develop more than one design option and decide after prototyping, testing, risk evaluation	
We systematically develop multiple designs and rule them out by prototyping, endurance testing, integration etc.	
Additional comments (optional):	

3.3.3 How do you rule out different design options for a product?	
Options	Select one
We only develop one design option for each product so there is no need to rule out other options	
We rule out design options on a theoretical base with techniques like FMEA, Brainstorming, Morphological box, etc.	
We choose the most promising design option based on personal experience and intuition	
We choose the final design option after ruling out other options through type testing, endurance testing, simulation (FEA)	
Additional comments (optional):	

3.3.4 How do you manage the interface between design and manufacturing/production?	
Options	Select one
Once the detailed design is finished the manufacturing/production department will receive the drawings to produce the parts	
Once the detailed design is finished the manufacturing/production department will be asked to give their comments	
Once the final concept is finished the manufacturing/production department will be asked to give their comments before starting the detailed design	
Once different design options are available the manufacturing/production department are involved for concept selection	
Additional comments (optional):	

3.3.5 Do you analyse and evaluate the leanness of design concepts with regard to manufacturing/production?	
Options	Select one
The underlying philosophy of "lean manufacturing" is not known in detail so a proper evaluation cannot take place	
The term "lean manufacturing" and its underlying concept is well known, but it is not formally integrated and practiced in the current product development process	
Different design concepts will be analyzed and evaluated with regard to lean manufacturing	
Additional comments (optional):	

3.3.6 The intention of "robust design" is to design a product in a way to make it somewhat resistant against so-called "noise factors" (environmental variation during the product's usage; manufacturing variation; component deterioration; market changes). How do you consider this when designing a new product?	
Options	Select one
The term "robust design" and its underlying concept is completely unknown and not considered in the current product development process	
The term "robust design" and its underlying concept is well known, but it is not formally integrated and practiced in the current product development process	
"Robust design" is not formally integrated in the current product development process but the underlying concept is practiced depending on the skill-level of the respective engineer	
"Robust design" is formally integrated to the current product development process. Possible "noise factors" are systematically explored and considered during the design of a product	
Additional comments (optional):	

3.4 Detailed design

3.4.1 When do you freeze the technical specification for a new product development?	
Options	Select one
The technical specification needs to be frozen before starting the development process and is not subjected to be changed during the project	
The technical specification needs to be frozen before starting the development process but can be adjusted as more information becomes available during the project	
The technical specification will be developed during the project as more information becomes available such as test results, feasibility evaluations, calculations, etc. (ensuring flexibility and minimum constraints)	
Additional comments (optional):	

3.4.2 How do you determine tolerances on manufacturing drawings?	
Options	Select one
The designer defines the tolerances based on his knowledge	
The designer usually defines the tolerances, partially he/she is consulting the manufacturing/production/supplier	
Tolerances will only be defined after confirmation from manufacturing/production/supplier	
The manufacturing/production or supplier is defining the tolerances and the designer is updating the drawings accordingly	
Additional comments (optional):	

4. Tools and Technology

4.1 Do you use Rapid Prototyping during the development of a product?	
Options	Select one
We rarely use rapid prototyping because it is too cost extensive	
We often use rapid prototyping but usually only for the final design	
We often use rapid prototyping in order to evaluate different design concepts and to rule out weak designs	
Additional comments (optional):	

4.2 Which of the following tools/techniques are formally implemented in the current product development process and help you during the design of a product?

Tools/Techniques	Frequency of use			Effectiveness		
	Never	Sometimes	Always	Not effective	Somewhat effective	Effective
FMEA (Failure Modes Effective Analyses)						
FTA (Failure Tree Analyses)						
FEA (Finite Element Analyses)						
Integration events / Design reviews / Quality Gates						
Trade-off-curves						
Limit curves						
A3 report						
Lessons learnt books						
Test-then-design method / test-to-failure						
QFD (Quality Function Deployment)						
Robust Design method						
Part-specific checklists						
TRIZ (Theory of inventive problem solving)						
Value Analyses / Value Engineering						
DFMA (Design for manufacture and assembly)						
Poka Yoke (Mistake Proofing)						
Competitor teardown analyses						
Checklists and quality matrices						
Learning focused problem solving (e.g. creating A3 template)						
Know-how database						
Reflection via lessons learnt / project shortcomings						
DA (Digital Assembly)						

4.3 Are your technological seamlessly integrated and adapted to your product development system?			
Tools	Level of integration		
	Fully integrated	Somewhat integrated	Not integrated
CAD system			
ERP system			
PDM system			
Knowledge database			
Test protocol database			

4.4 What is your experience with the company´s Knowledge database in relation to product development performance?	Bad - Not useful	Occasionally Beneficial	Very Good - Recommended
Additional comments (optional):			

4.5 Which of the following activities do you usually apply before starting the design of a new product?	
Options	Select as appropriate
Market research	
Patent research	
Analyzing competitor products	
Searching for similar projects that have been done in the company in order to use that as a base for the new development	
Usually there is no time to do one of the above activities and I`m starting immediately with the detailed design of the most promising solution variant	
Additional comments (optional):	